TDEM SURVEYS AT THE
LIHI LANI PROJECT SITE
PUPUKEA, KOOLAULOA DISTRICT
OAHU, HAWAII

TIME DOMAIN ELECTROMAGNETIC (TDEM) SURVEYS AT THE LIHI LANI PROJECT SITE PUPUKEA, KOOLAULOA DISTRICT OAHU, HAWAII

Prepared For:

Kuilima Development Company
1001 Bishop St.
Puauhi Tower
Honolulu, HI 96813

Prepared By:

Blackhawk Geosciences, Inc.
17301 West Colfax Avenue, Suite 170
Golden, CO 80401

(BGI Project #92029)

July 15, 1992

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1.0 INTRODUCTION

This report contains the results of time domain electromagnetic (TDEM) surveys conducted at the Lihi Lani Project Site, Pupukea, Koolauloa District, on the Island of Oahu, Hawaii. The survey was performed by Blackhawk Geosciences, Inc. (BGI) for Kuilima Development Company during June 1992.

The overall objective of the survey was to assist in defining potential fresh water resources at the project site. The two major factors which influence the location and availability of fresh ground water in this geologic setting are (i) the elevation of the fresh water - salt walter interface for basal ground water occurrences, and (ii) the location and attitude of potential ground water damming structures (e.g., dikes) and aquitards. Thus, the specific objectives of this survey were to

- map the fresh water - salt water interface underlying the survey area, and

- identify and map geologic structures or lithologic units which may affect ground water distribution.

In TDEM surveys the electrical resistivity of the subsurface is measured. Previous TDEM surveys on the Hawaiian Islands have shown large resistivity contrasts to occur between volcanics saturated with fresh water and saline water. In most cases, also significant resistivity contrasts exist between geologic structures and between weathered and unweathered volcanics.

2.0 DATA ACQUISITION

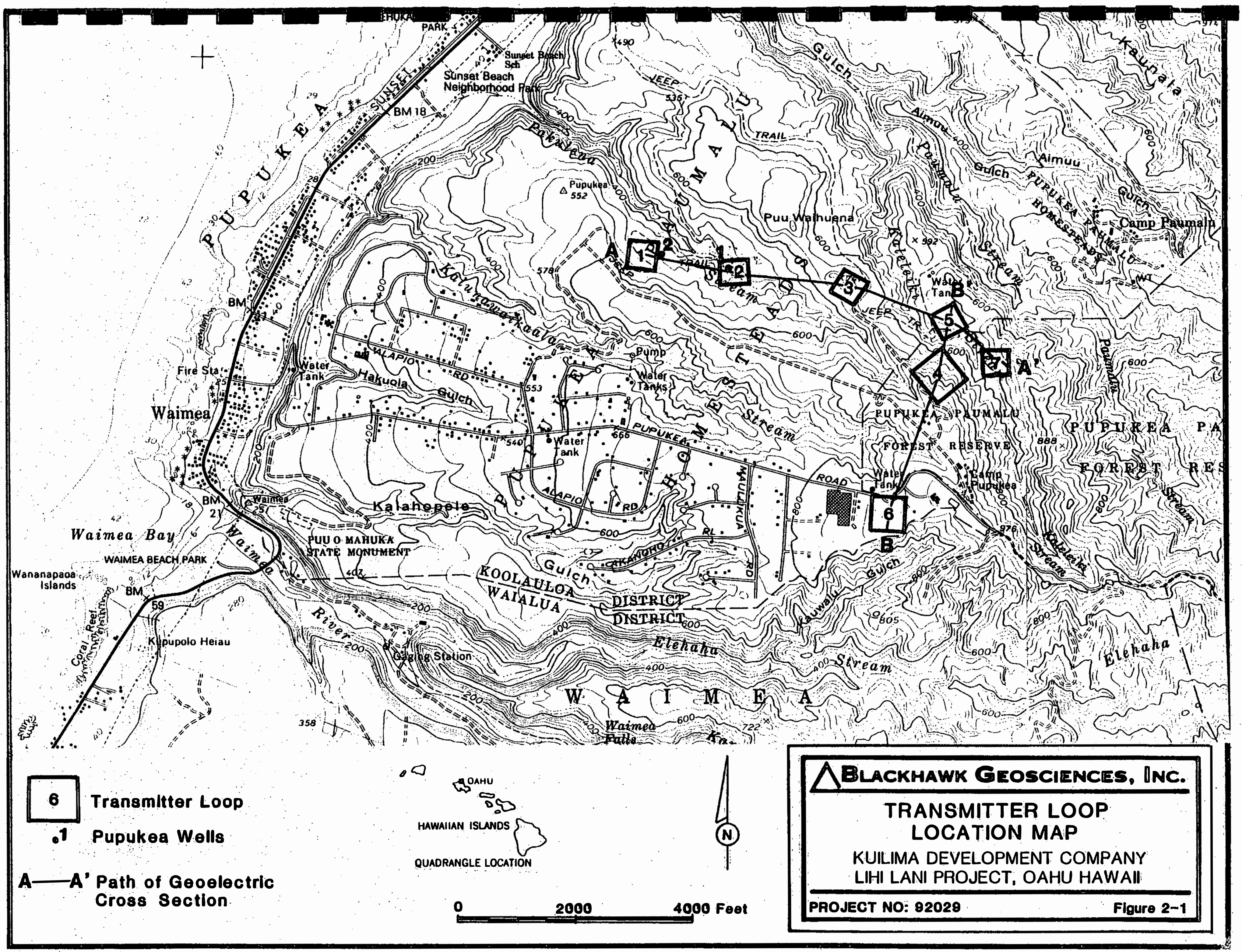
A crew consisting of two BGI geophysicists acquired the field data. A daily log of field activities is given in Table 2-1.

Table 2-1. Daily log of field activities

Date (1992)	Activity
June 10	Mobilize crew and equipment from Denver, CO to Honolulu, HI.
June 11	Acquire data at soundings 1E and 2E.
June 12	Acquire data at soundings 3E and 4E.
June 13	Acquire data at sounding 5E.
June 14	Demobilize equipment to other projects on Island of Hawaii.
June 28	Mobilize equipment to Oahu from Hawaii.
June 29	Acquire data at soundings 6E and 7E.
June 30-July 1	Demobilize equipment and crew from Oahu to Denver, CO.

The TDEM data were acquired using the central-loop configuration (central-loop soundings). With this configuration, measurements are recorded with the receiver located at the center of square transmitter loops laid on the ground surface. The transmitter loops are constructed with 10 gauge insulated copper wire and the dimensions of the loop depend upon the required exploration depth (larger dimensions for deeper exploration depth). For soundings at the Lihi Lani Project Site transmitter loop sizes of 500 ft by 500 ft up to 750 ft by 750 ft were used to meet the survey objectives. A total of 7 soundings were made at the site as shown on Figure 2-1. Positions of soundings were constrained by jeep trail access and available property. In addition, the measurement locations were positioned, as much as possible, to avoid pipelines and power lines which affect data quality. Survey elevation control and location was based on the 7.5 minute, U.S.G.S. topographic map (Waimea, Hawaii) and elevations were checked with a barometric altimeter.

The Geonics EM-37 TDEM system was used for the survey, with a transmitter current between 16 and 19 amperes at base frequencies of 3 Hz and 30 Hz. At the center of each transmitter loop the time derivative of the vertical magnetic field was recorded. The data from each sounding was stored in the field on a DAS 54 data logger and subsequently transferred to a PC-386 for nightly processing.



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TRANSMITTER LOOP LOCATION MAP

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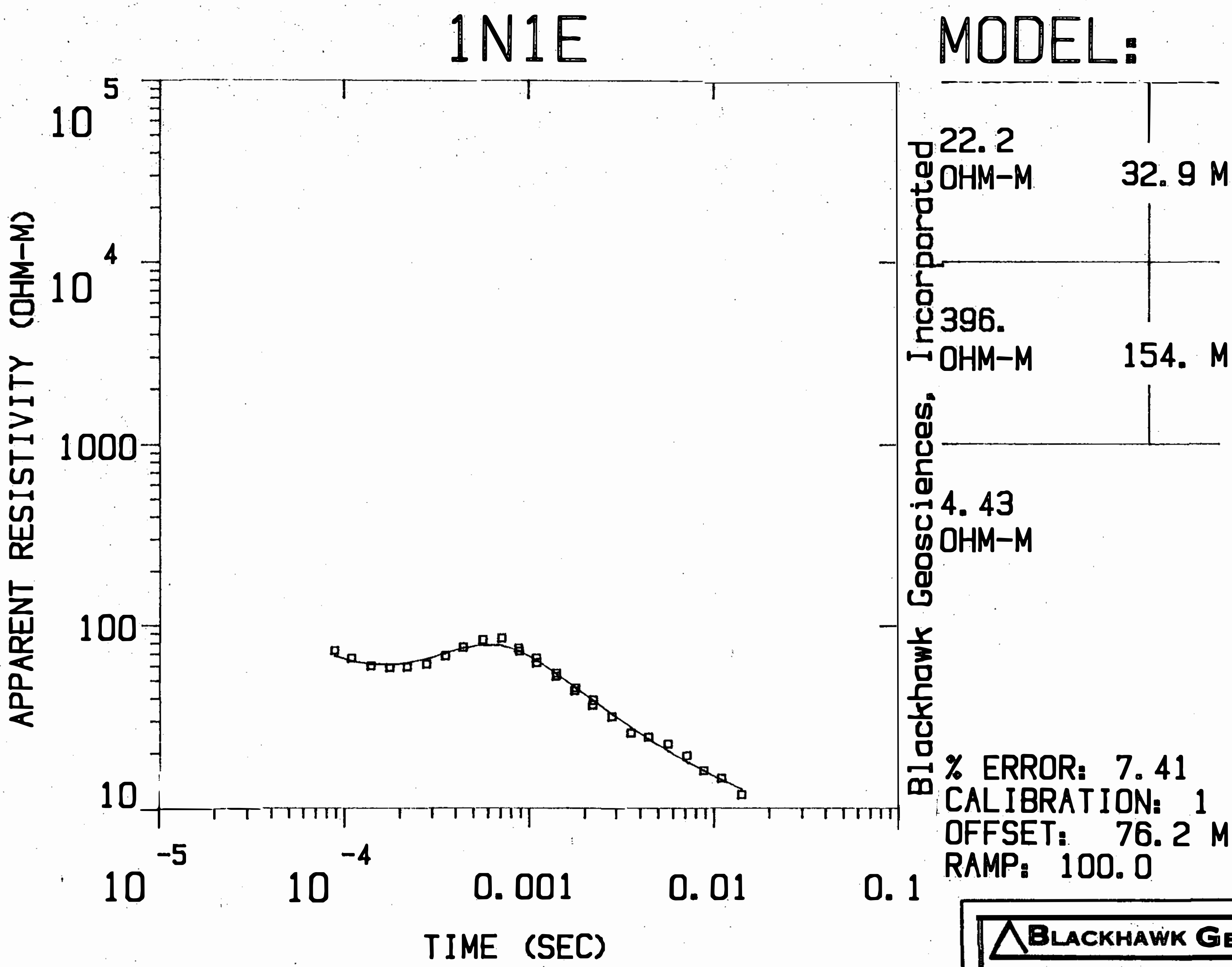
PROJECT NO: 92029 Figure 2-1

3.0 DATA PROCESSING

The first step in data processing is to average the emfs recorded at opposite receiver polarities. Next, the recordings made at different amplifier gains and frequencies were combined to give one transient decay. The emfs in the various time gates of the decay curves are subsequently entered into a ridge regression inversion program to obtain a one-dimensional (1-D) geoelectric section that matches the observed decay curve.

The inversion program requires an initial model for the geoelectric section. This model is usually derived from approximate matching of apparent resistivity curves with model curves from a series of albums of model curves or from a knowledge of the geoelectric section obtained from drill holes. The inversion program is then allowed to adjust the model to improve the fit. This involves the adjustment of resistivities and thicknesses of the layers within the geoelectric model. The inversion program does not change the total number of layers within the model but all other parameters float freely, or optionally can be held constant. To determine the influence of number of layers on the solution, separate inversions with a different number of layers are run.

An example of the output of the inversion program for a typical sounding is given in Figure 3-1. The measured data points (in terms of apparent resistivity) are superimposed on a solid line. The solid line represents the computed forward model for the geoelectric section shown on the right. This geoelectric section is the best match obtained by the inversion program. Tabulated inversion parameters consisting of measured data, computed data for best match solution, and inversion error are given in Figure 3-2. The geoelectric section in turn is translated into hydrogeologic information by establishing a relationship between resistivity and hydrogeologic units. The principles of TDEM are explained in Appendix A. Inversion plots and tables for all soundings are given in Appendix B.



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EXAMPLE INVERSION RESULTS

SOUNDING 1N1E

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Figure 3-1

1N1E

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		152.4	500.0		
22.24	32.9	119.5	392.2	1.5	1.5
395.89	154.3	-34.8	-114.0	0.4	1.9
4.43					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	7.30E+01	6.86E+01	6.509	
2	1.10E-04	6.63E+01	6.40E+01	3.484	
3	1.40E-04	6.01E+01	6.14E+01	-2.065	
4	1.77E-04	5.88E+01	6.11E+01	-3.675	
5	2.20E-04	5.94E+01	6.25E+01	-4.939	
6	2.80E-04	6.17E+01	6.59E+01	-6.299	
7	3.55E-04	6.85E+01	7.06E+01	-2.924	
8	4.43E-04	7.64E+01	7.53E+01	1.493	
9	5.64E-04	8.36E+01	7.86E+01	6.349	
10	7.13E-04	8.53E+01	7.78E+01	9.666	
11	8.81E-04	7.54E+01	7.28E+01	3.525	
12	8.90E-04	7.25E+01	7.25E+01	0.055	
13	1.10E-03	6.63E+01	6.48E+01	2.293	
14	1.10E-03	6.26E+01	6.46E+01	-3.190	
15	1.40E-03	5.29E+01	5.49E+01	-3.538	
16	1.41E-03	5.49E+01	5.46E+01	0.587	
17	1.77E-03	4.40E+01	4.61E+01	-4.464	
18	1.80E-03	4.56E+01	4.56E+01	-0.041	
19	2.20E-03	3.66E+01	3.92E+01	-6.443	
20	2.22E-03	3.92E+01	3.88E+01	0.892	
21	2.80E-03	3.17E+01	3.28E+01	-3.440	
22	3.55E-03	2.58E+01	2.78E+01	-7.030	
23	4.43E-03	2.46E+01	2.39E+01	2.628	
24	5.64E-03	2.25E+01	2.06E+01	9.144	
25	7.13E-03	1.94E+01	1.79E+01	8.210	
26	8.81E-03	1.60E+01	1.59E+01	0.304	
27	1.10E-02	1.45E+01	1.43E+01	1.957	
28	1.41E-02	1.19E+01	1.27E+01	-6.269	

R: 76. X: 0. Y: 76. DL: 152. REQ: 84. CF: 1.0000
CLHZ ARRAY, 28 DATA POINTS, RAMP: 100.0 MICROSEC, DATA: 1N1E
1106 001N 001E Z OPR XTL H 2 8+100
Ch.21 = 0.095 Ch.22 = 0.089 Ch.23 = 16 Ch.24 =
RMS LOG ERROR: 3.10E-02, ANTILOG YIELDS 7.4078 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.22				
P 2	0.01	0.00			
P 3	0.00	0.00	0.02		
T 1	-0.15	-0.01	0.01	0.12	
T 2	0.05	0.01	0.04	0.01	0.31
	P 1	P 2	P 3	T 1	T 2

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EXAMPLE INVERSION TABLE
SOUNDING 1N1E
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PROJECT NO: 92029 **Figure 3-2**

4.0 HYDROGEOLOGIC SETTING

General

The hydrologic setting at the Lihi Lani Project Site is described in a report by John F. Mink (1988) entitled "Groundwater Conditions, Pupukea-Paumalu, Oahu". Subsequent to this report, two wells were drilled on the property and the results from these wells are described in a report by John F. Mink (1989) entitled "Pupukea Golf Course Wells, Summary of Pump Test Results, Recommendations Pump Size and Setting". Much of the following information was extracted from these two reports.

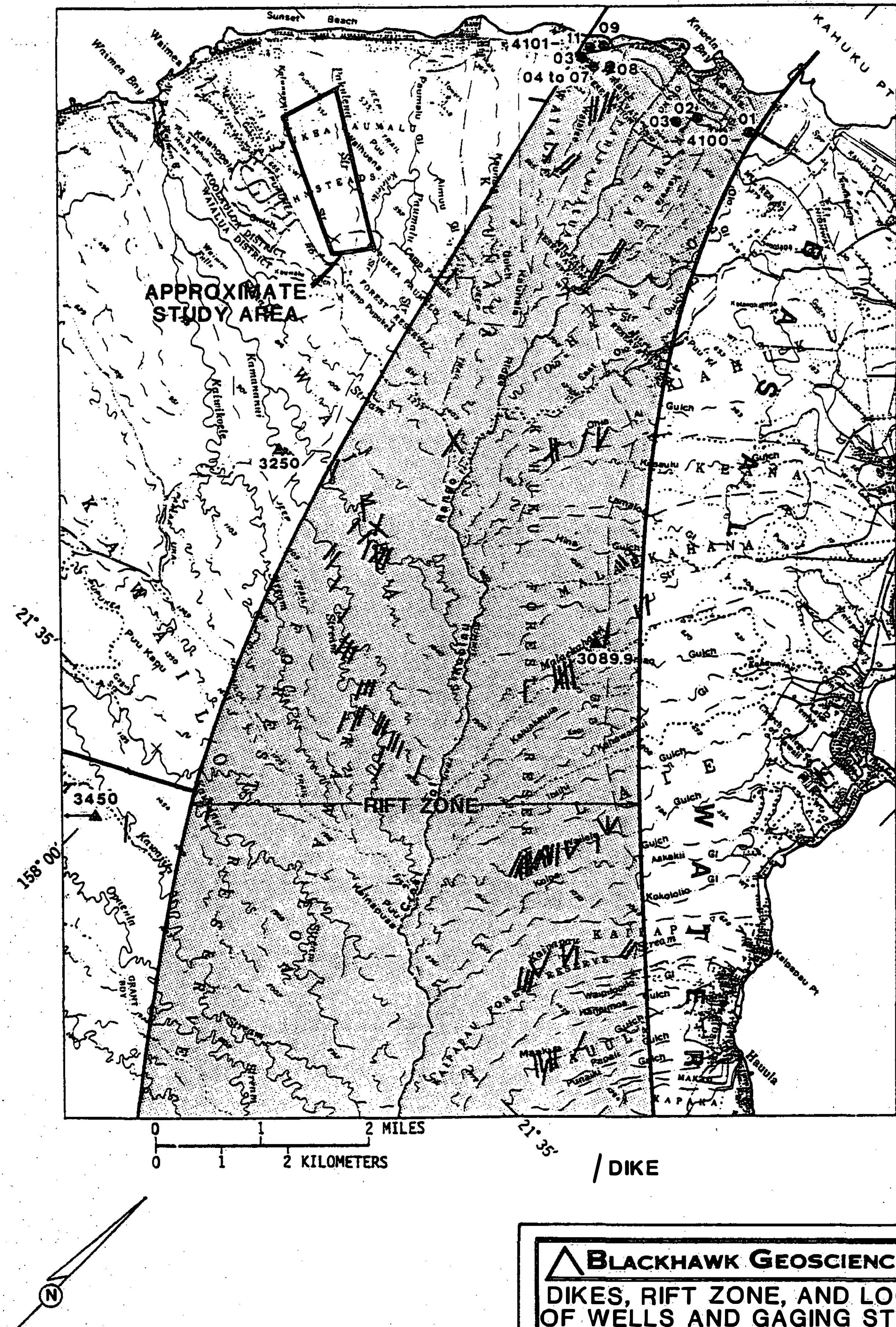
Hydrogeology

The Pupukea-Paumalu region is placed in the North Sector of Oahu in the Kawailoa Aquifer System which identifies the aquifer type as unconfined, basal in lava of the Koolau volcanic series. The principle aquifer in the system is a thin basal lens of fresh to brackish water floating on sea water. This basal lens is the least robust in northern Oahu, having a head of less than 3 ft at a distance of 1 to 2 miles from the coast.

The potential for dike-confined ground water in the region is examined in "Evaluation of Major Dike-Impounded Ground-Water Reservoirs, Island of Oahu" (K.J. Takasaki and J.F. Mink, 1985; U.S.G.S. Water-Supply Paper 2217). In this evaluation potential ground water damming structures (dikes and rift zones) were mapped east of the property as shown on Figure 4-1. The nearest mapped dike or rift zone occurs near Camp Paumalu (about 3,000 ft northeast of the nearest TDEM sounding). Takasaki and Mink report that nearly all of the dikes mapped are vertical and have strikes ranging from $N10^0W$ to $N40^0W$.

Results of Boreholes

Two wells were drilled on the property in the Pakulena Valley in 1988. The locations of these wells are shown on Figure 2-1. Mink (1989) reports that the wells show a salinity of about 300 mg/l at a pumping rate of 500 ppm. Static water level (heads) in the wells is 3.8 and 3.7 ft for wells 1 and 2, respectively, which is indicative of a low-head basal lens. Drawdown of the wells during the pump tests was negligible, and recovery was virtually instantaneous.



From: Evaluation of Major Dike-Impounded Ground-Water Reservoirs, Island of Oahu (Takasaki and Mink 1985) USGS Water Supply Paper 2217

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DIKES, RIFT ZONE, AND LOCATION OF WELLS AND GAGING STATIONS, NORTHERN END SUBZONE

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PROJECT NO: 92029 — Figure 4-1

5.0 RESULTS

5.1 GENERAL

The main objective of the geophysical survey at the Lihi Lani Project Site was to infer from the resistivity layering obtained from TDEM soundings, the depth to salt water and the thickness of the basal fresh water lens. Another objective of the survey was to detect and map potential ground water damming structures. The translation of resistivity layering into hydrologic information is generally accomplished by two methods:

(1) One method is to use available knowledge about the relation between resistivity values and local hydrology. From more than fifteen previous TDEM surveys in the Hawaiian islands, it has been shown that dry and fresh water saturated volcanic rocks have high resistivities, typically greater than 500 ohm-m. Conversely, volcanic rocks saturated with salt water exhibit resistivities typically less than 5 ohm-m. Weathered volcanics or intrusives and ash flows often display intermediate resistivities (10 to 100 ohm-m). Using this knowledge, the characteristic ranges of resistivities expected for local geohydrologic units in the Lihi Lani study area are shown on Figure 5-1.

    It should be noted that some overlap in resistivity does occur. In these cases, often other factors can be used to infer the geologic/hydrologic unit in question. For example, a very low resistivity unit (e.g., less than 10 ohm-m) occurring at an elevation above seal level is assumed to be caused by weathered rock formations rather than saline water saturated formations.

(2) Another method is to calibrate the geophysical interpretation at a well. In this case two wells were available for comparison. On Figures 5-2 and 5-3 a comparison of the TDEM results and borehole driller's logs are shown for Pupukea boreholes #1 and #2, respectively (TDEM soundings 1N2E and 1N1E, respectively). On these figures the resistivity stratification derived from the inversion of the TDEM data is given on the left and the information taken from the drillers logs is given on the right.

On Figure 5-2 the TDEM data were interpreted using a three-layered model. In this case, the uppermost layer in the inversion (38 ohm-m) correlates with the Red Clay and Decomposed Rock and Soil units listed in the drillers log. The second layer in the inversion (188 ohm-m) correlates with unaltered and competent rocks listed in the drillers logs. The third layer in the inversion (4.3 ohm-m) is beyond the total depth of the drill hole, and is interpreted to be caused by saline saturated volcanics based upon its' low resistivity value. Static water level (head) calculated from the TDEM results using the Ghyben-Herzberg relation is 2.15 ft. The head measured in the borehole was 3.8 ft which is in good general agreement with the TDEM results.

On Figure 5-3 the uppermost layer in the inversion (22 ohm-m) corresponds to the Brown Soil Boulders and Clay (saprolite) taken from the drillers log. The second layer in the inversion (396 ohm-m) corresponds to the Puka and Hard Rock noted in the driller log. The third layer in the inversion (4.4 ohm-m) is beyond the total depth of the drill hole, and is interpreted to be caused by saline-saturated volcanics. Head calculated from the TDEM results is 2.85 ft. Head reported from the borehole was 3.7 ft which is again in good general agreement with the TDEM results. Thus, from the comparison of the TDEM inversions and drillers logs the relationship between characteristic ranges of resistivities and geohydrologic units shown in Figure 5-1 is confirmed.

5.2 GEOELECTRIC SECTIONS

General

The inversion results (resistivity layering) from the TDEM soundings have been combined in Figure 5-4 to produce two geoelectric sections. The path of the geoelectric sections is shown in Figure 2-1.

Geoelectric Section A-A' (West to East)

The results of Pupukea wells #1 and #2 have been superimposed upon the geoelectric cross-section A-A' in the upper part of Figure 5-4. In this geoelectric section the uppermost layer across the section is interpreted to correspond to the saprolite, and decomposed rock layers detected in the Pupukea wells. This layer apparently thickens towards the east part of the section and is approximately 300 ft thick near stations 5E and 7E. The second layer in the section is interpreted as unaltered volcanics and where this layer extends below sea level it is expected to be saturated with fresh-brackish water. This layer extends below sea level at 1E, 2E and 3E and is deepest at 3E (approximately 140 ft below sea level).

At stations 1E, 2E and 3E the deepest layer in the section is interpreted as saline saturated volcanics (i.e., at these stations the fresh-brackish ground water resource is in the basal mode). At stations 5E and 7E the lower-most layer in the section shows low resistivities (7.7 and 4.9 ohm-m) and lies 71 ft below sea level at 5E and 104 ft above sea level at 7E. Because this layer extends above sea level it is interpreted to be caused by clays, extremely altered volcanics, or a geologic structure (e.g., dike or rift zone). The apparent dip of this unit between 5E and 7E is approximately 10^0 to the west.

Geoelectric Section B-B' (South to North)

Geoelectric cross-section B-B' is given on the lower part of Figure 5-4. The section between 4E and 5E is similar to the eastern part of Section A-A' in that the lower-most layer in the section is interpreted to be caused by clays, extremely altered volcanics, or a geologic structure. The sounding at 6E shows a significantly different geoelectric section than any of the other soundings. Because of this difference, it may be possible that a geologic structure exists between 6E and 4E (possibly within the Kalunawaikaala Stream Gulch). At 6E all layers in the section have moderate or low resistivities and the deepest layer in the section shows a very low resistivity (2.5 ohm-m) and lies well above sea level (226 ft A.S.L.). This deep conductive layer appears to extrapolate to the deep conductive layers detected at stations 4E and 5E and thus may be correlated.

Correlation of geoelectric units between 6E and 4E is not clear and possible correlations are shown on Figure 5-4 as dashed (questionable) correlations. Because of the relatively low resistivities in the upper sections at stations 6E and 4E, these layers are interpreted as saprolite, clays, and altered volcanics. The thickness of this unit is large (approximately 620 ft at 6E and 500 ft at 4E).

Equivalence in Inversion Solutions

The parameters derived for the geoelectric section by the ridge regression inversion are not unique, but generally a range of values will equally fit the observed data within the overall RMS error. This phenomena is called equivalence, and the range of equivalence differs for each parameter of a geoelectric section. It is a measure of how well each parameter is resolved, and an example equivalence analysis for TDEM sounding 1N5E is given in Figure 5-5. This figure shows both graphically and in the table, the upper and lower bound for each parameter of the geoelectric section. Thus, for TDEM sounding 1N5E the largest range of equivalence is in determining the depth to and the resistivity of the second layer (unaltered volcanics). The depth to the top of this layer may vary from 82 m to 108 m (268 to 355 ft), and its resistivity from 135 to 354 ohm-m and still result in the same RMS error. The results of the equivalence analysis for the other soundings is similar, i.e., the largest equivalence is in the depth to and resistivity of the second layer (unaltered volcanics). The range of equivalence for the parameters of the overlying and underlying layers are relatively small. In particular, the total depth to and the resistivity of the conductive third (deepest) layer in all soundings is well resolved. Equivalence analysis for all soundings are given in Appendix B.

Modeling Studies

In the geoelectric cross-section A-A' on Figure 5-4, a basal ground water hydrology system is expected to exist from 1E to 3E. At stations 5E and 7E the section is underlain by a dipping conductive layer which extends above and below sea level. Because this layer is interpreted to be caused by clays, altered volcanics, or a possible geologic structure, it may form an aquitard. Therefore, further information about the thickness of this layer is important for hydrologic consideration.

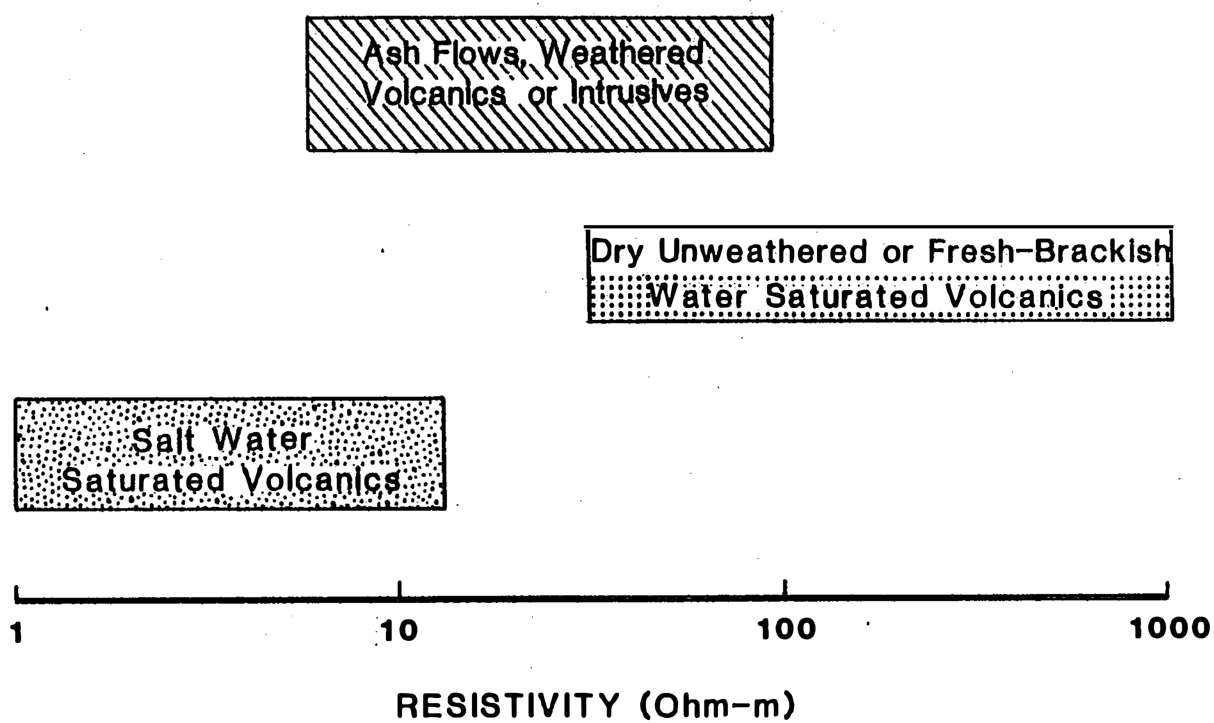
To determine the minimum thickness of the dipping conductive layer, computations were performed using the data from station 1N7E. The minimum thickness is estimated using the following procedure:

(1) The best fit model for the sounding is used as a starting model.

(2) A layer with a resistivity of 100 ohm-m (corresponding to unaltered volcanics) is placed below the measured section.

(3) Next, by iterations the minimum depth at which the 100 ohm-m layer, placed below the observed section, causes measurable differences in emf is computed.

An example of computing minimum thickness of the dipping conductive unit is given on Figure 5-6. On this figure the thickness of the third layer is varied in steps of 100 m from 400 m to 100 m. In this example a third layer thickness of 100 m results in an RMS error of 9.7%, which would be readily measurable. Thus, the conservative minimum thickness of the dipping conductive layer is about 100 m or 328 ft.



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CHARACTERISTIC RESISTIVITY RANGES

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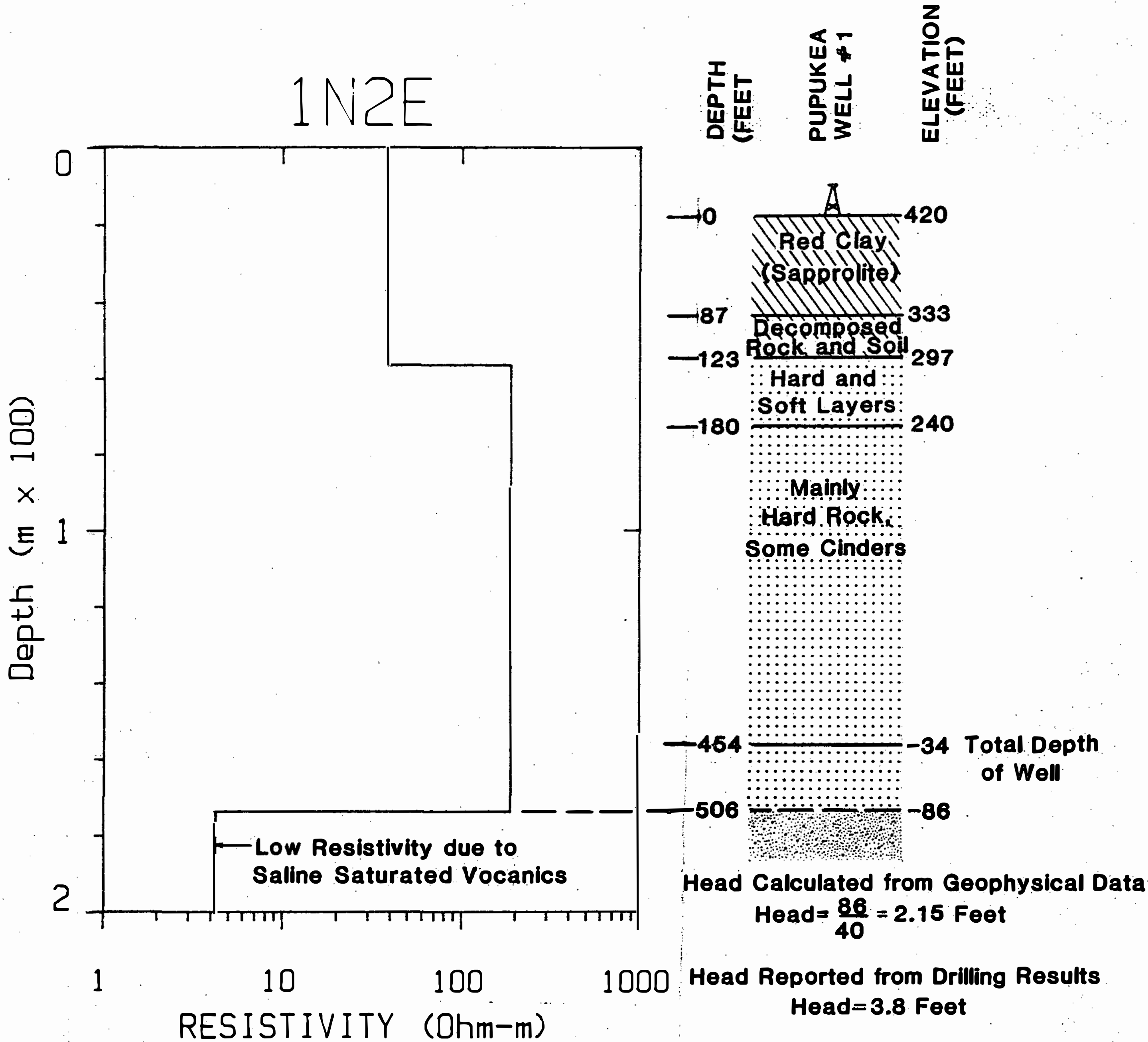

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COMPARISON OF PUPUKEA WELL #1 AND TDEM SOUNDING 1N2E

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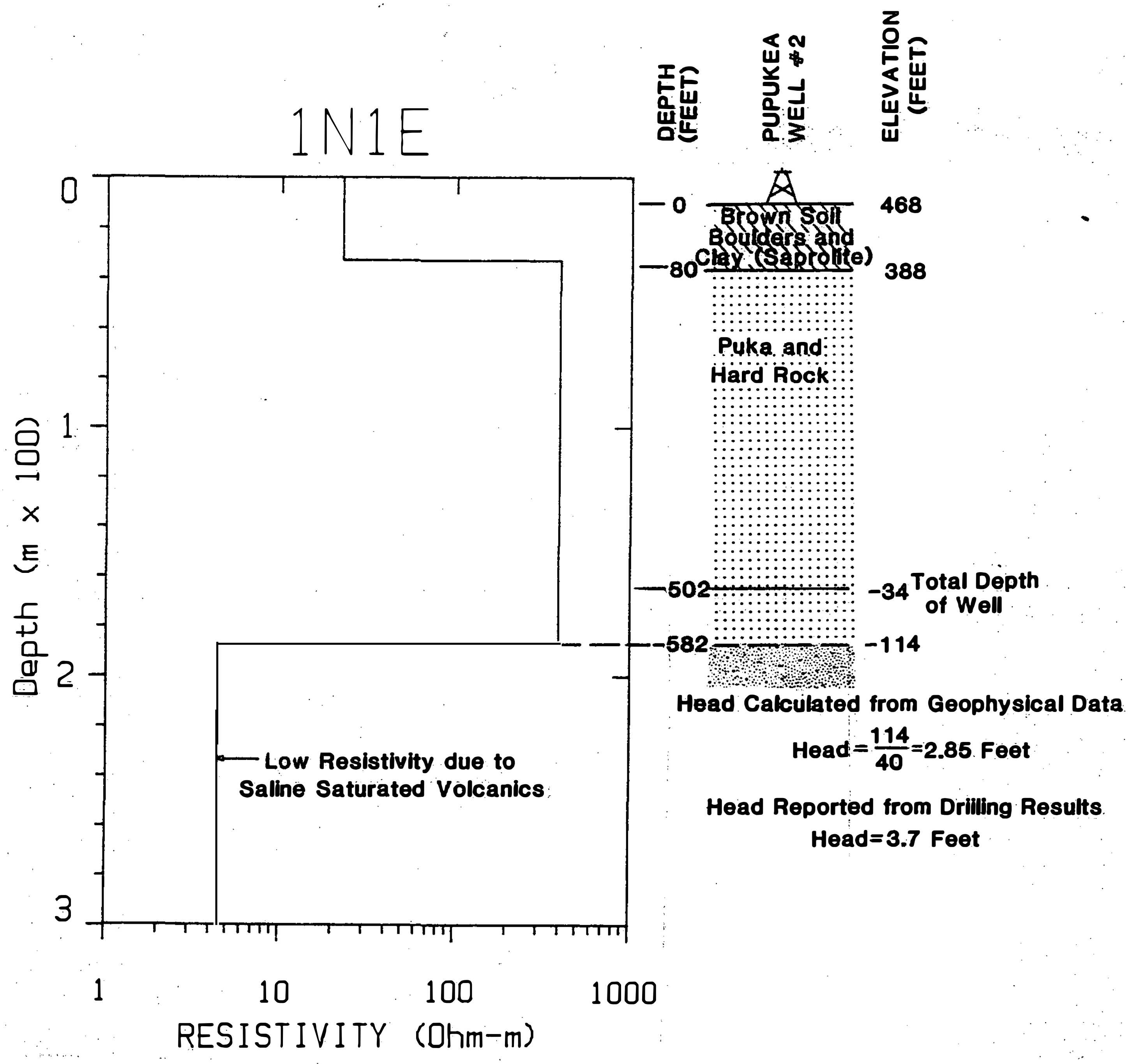
PROJECT NO: 92029 **Figure 5-2**



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COMPARISON OF PUPUKEA WELL #2 AND TDEM SOUNDING 1N1E

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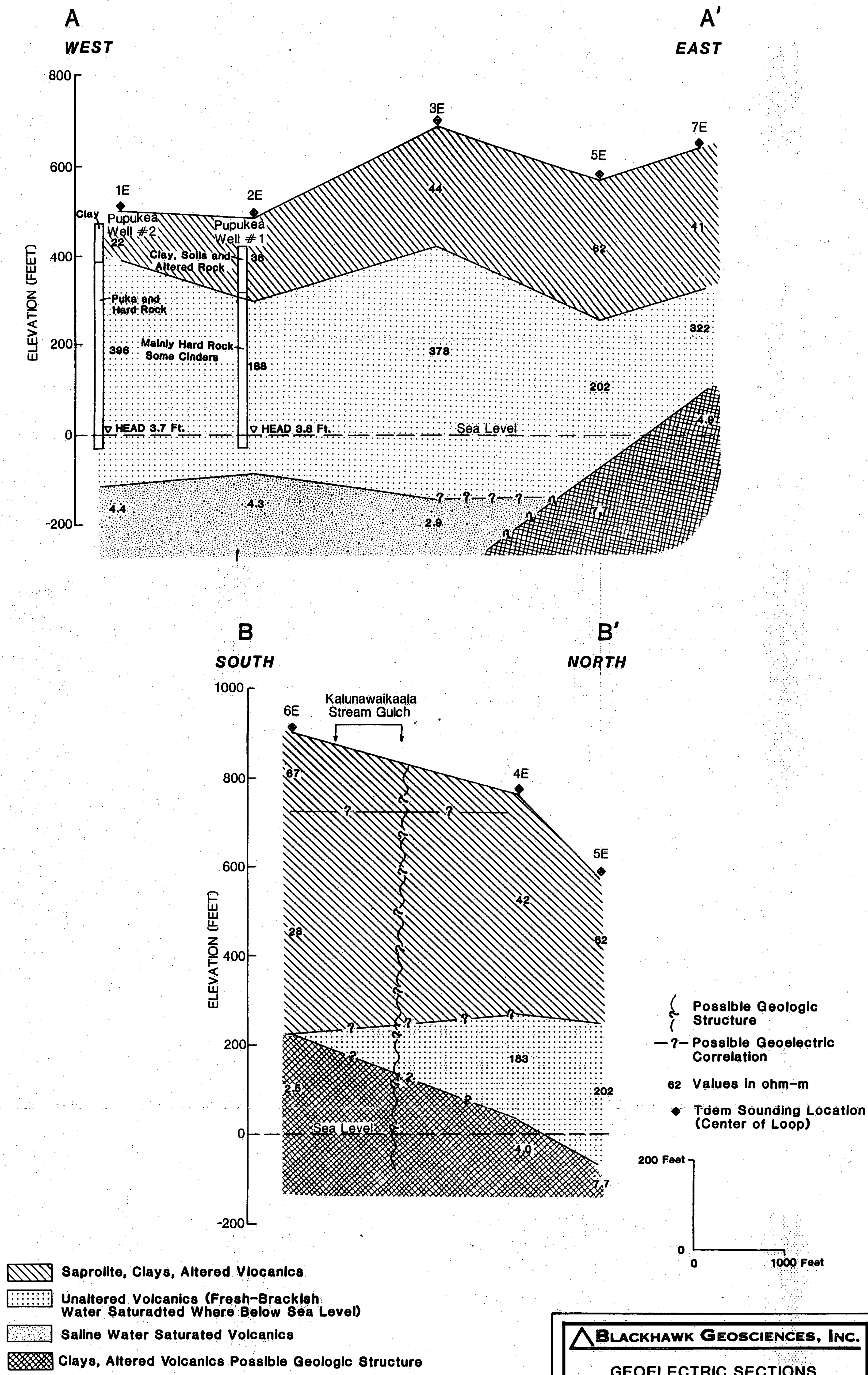
PROJECT NO: 92029

Figure 5-3



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GEOELECTRIC SECTIONS

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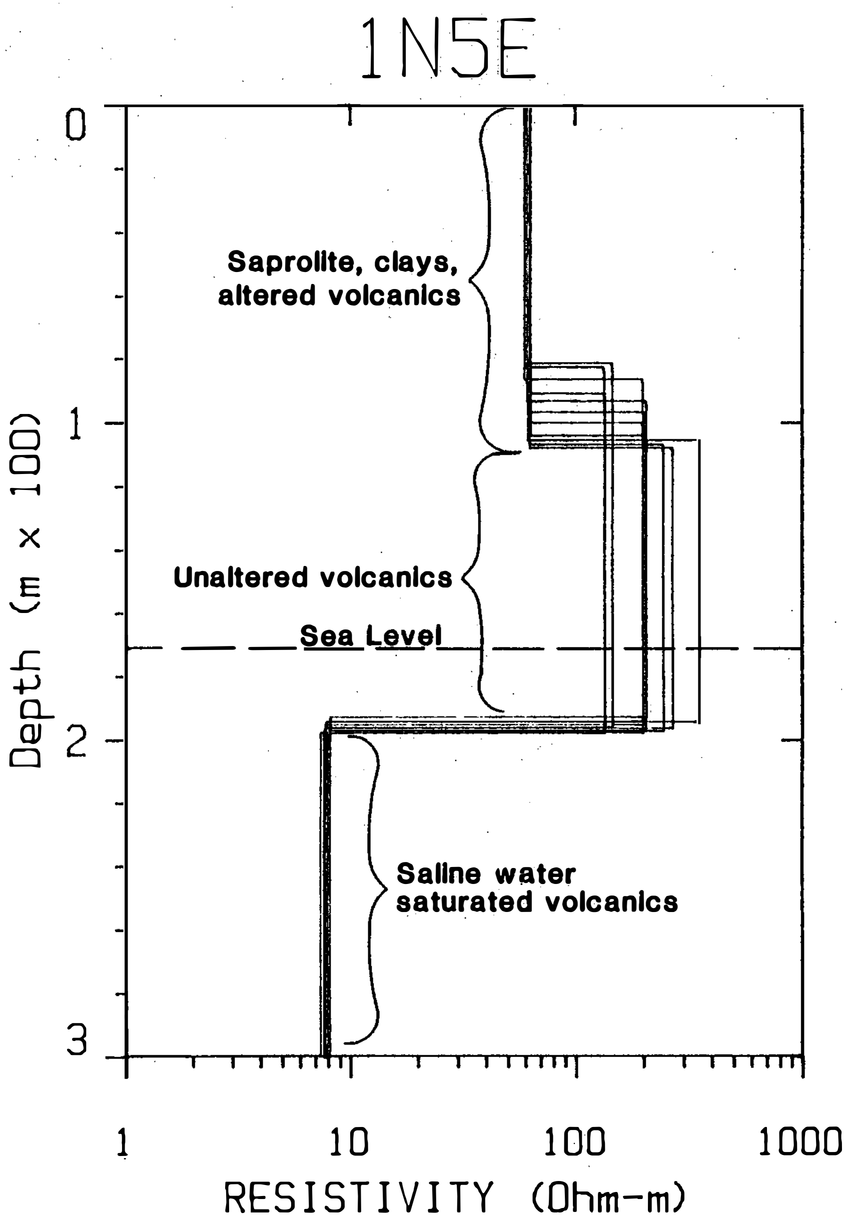
Figure 5-4



PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	59.589	61.717	63.133
	2	134.616	202.340	353.815
	3	7.321	7.683	8.091
THICK	1	81.595	96.995	108.161
	2	88.299	98.435	115.189
DEPTH	1	81.595	96.995	108.161
	2	192.955	195.431	198.042

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EQUIVALENCE IN INVERSION SOLUTION FOR SOUNDING 1N5E

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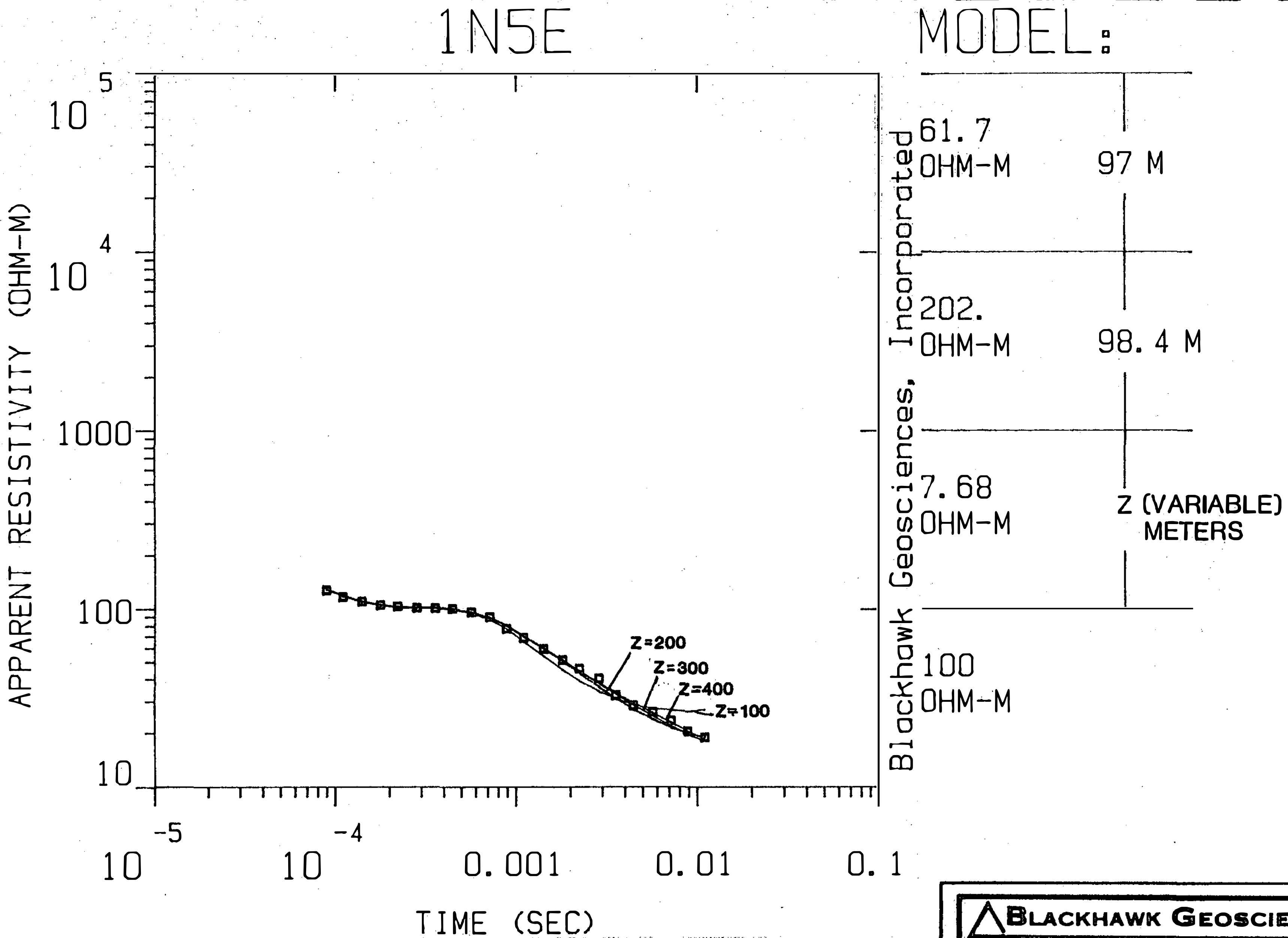
PROJECT NO: 92029 Figure 5-5



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COMPUTATION OF MINIMUM THICKNESS OF LAYER 3

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LIHI LANI PROJECT, OAHU HAWAII

PROJECT NO: 92029 **Figure 5-6**

6.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the geophysical survey at the Lihi Lani Project Site was to infer from the resistivity layering obtained from TDEM soundings, the depth to salt water and the thickness of the basal fresh water lens. Another objective of the survey was to detect and map potential ground water damming structures.

In this survey, basal mode ground water is interpreted to exist beneath stations 1E, 2E and 3E on the west side of the property. At these stations the basal brackish/fresh water lens interpreted from the TDEM data is modest (heads calculated from Ghyben-Herzberg relation are 2.85, 2.15 and 3.61 ft) and in good general agreement with the results obtained from the Pupukea wells #1 and #2 (heads 3.8 and 3.7 ft, respectively). The thickness of the saprolite/soil horizon interpreted from the TDEM soundings is also in good agreement with the drillers logs for the two wells. Saprolite/soil horizon thickness derived from the TDEM soundings apparently thickens to the east (≈ 300 ft thick at station 7E) and to the south (> 450 ft thick at stations 4E and 6E).

The four soundings on the east side of the property (4E, 5E, 6E and 7E) detect a buried dipping conductive layer which occurs below sea level at station 5E and above sea level at stations 4E, 6E and 7E. This layer is interpreted to be caused by clays, altered volcanics, or geologic structures, and thus may act as an aquitard or ground water damming unit. Model studies show that this dipping conductive unit has a thickness of 100 m (328 ft) or greater. From the relatively few TDEM soundings this unit appears to strike at approximately N45^{0}E and dip to the northwest at about 8 to 10^0. This orientation and dip is contrary to that expected from dikes and rift zones mapped near Camp Paumalu (N10^{0}W to N40^{0}W - Takasaki and Mink, 1985) about 3,000 ft northeast of TDEM sounding 1N7E. Thus, this unit may more likely be caused by clays or extreme alteration of volcanics rather than geologic structure. An approximate extrapolation of this unit to the surface would place its outcrop at 4,000 to 5,000 ft southeast of the eastern-most soundings (6E and 7E). During the field survey, attempts were made to gain access to property southeast of Camp Pupukea to further define this unit, but poor road access and locked gates at the Forest Reserve precluded these measurements. Additional soundings in this area would be recommended if more detailed information about the attitude (strike and dip) and thickness of this unit is desired.

PRINCIPLES OF TIME DOMAIN EM

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Question.-- What is TDEM?

Answer.-- TDEM is a surface geophysical method for determining the lateral and vertical resistivity variation (geoelectric section) in the subsurface.

Question.-- What useful information can be derived from the geoelectric section?

Answer.-- Electrical resistivity can be used as an indicator for mapping several important objectives in the subsurface, such as:

1. Presence of contaminants. Dissolved solids in ground water decrease formation resistivities, so that industrial contaminant plumes and differences in salinity (e.g., salt water intrusion) can often be delineated from geoelectric sections.

2. Soil and rock types. Clays and clay shales, and formations of low hydraulic permeability, have lower resistivities than formations of high hydraulic permeability, such as sands and gravels, sandstones, basalts, and high porosity limestones. The geoelectric section can, therefore, be used to map continuity of clay and clay shale lenses.

3. Fractures and shear zones. Such zones are conduits for ground water flow and contaminant migration, and they are often characterized by zones of low resistivity. The reasons for the lower resistivities of these zones are infilling of the fracture zones by clay gouge, alteration of wall rock, and higher water contents.

Question.-- What advantages does TDEM have over other electrical and electromagnetic methods, such as resistivity (direct current) and electromagnetic conductivity profiling with the Geonics EM-31 and EM-34?

Answer.-- The advantages of TDEM over other electrical and electromagnetic methods are

- better vertical and lateral resolution
- lower sensitivity to geologic noise (see page 5)
- the ability to explore below highly conductive layers (e.g., brine saturated layers and clay lenses).

Some of the most frequently asked questions about TDEM and their answers are given below.

Question.-- Are the principles of TDEM similar to electromagnetic induction profiling, such as used in the Geonics EM-31 and EM-34?

Answer.-- Yes, the principles of electromagnetic induction profiling in the frequency domain (FDEM), used in the Geonics EM-31 and EM-34, are in many ways similar to the principles of TDEM.

An important difference between FDEM and TDEM is the current waveform driven through the transmitter loops. It is a continuous, harmonic-varying current in FDEM, and a half-duty cycle waveform in TDEM.

Question.-- Why does the current waveform of the transmitter make a large difference?

Answer.-- The large difference results from the fact that in FDEM the secondary magnetic field due to ground currents is measured when the transmitter current is on, and in TDEM when the transmitter current is off. In both cases the time-variant current driven through the transmitter causes a time-variant primary magnetic field. Associated with this primary magnetic field is an induced electromotive force (emf) that causes eddy current flow in the subsurface. The intensity of these currents is used to determine subsurface conductivities. The induced emf is a harmonic-varying function in FDEM and consists of narrow pulses in TDEM.

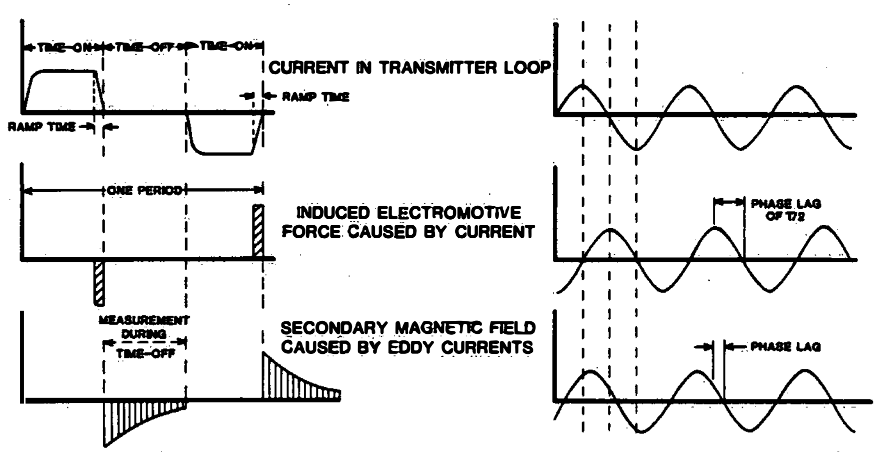

Fig. 1. System waveforms in time domain EM (TDEM) and frequency domain EM (FDEM).

The receiver measures the emf due to the secondary magnetic field of these eddy currents induced in the subsurface, and in the case of FDEM, the emf measured by the receiver is the sum of (1) the primary magnetic field (emf_p due to currents in the transmitter), and (2) the secondary magnetic field (emf_s due to eddy current flow in the ground). Thus,

$$emf_t = emf_p + emf_s$$

where subscript t, p and s refer to total, primary, and secondary magnetic field, respectively. Clearly, emf_s is the only component containing information about the subsurface. Unfortunately, in most situations, the amplitude of emf_s is only one part in 10^4 parts of emf_p. Thus, in FDEM, a small component of emf containing all the useful information about the subsurface must be measured in the presence of a large component containing no information.

In the EM-31 and EM-34 ground conductivity is determined by measuring only the component of emf_s that is in quadrature phase (90^o out-of-phase) with emf_p. Unfortunately, theory shows that the in-phase component is more sensitive to ground conductivity. Measuring only the quadrature phase component limits the accuracy, exploration depth, and utility of FDEM systems.

TDEM improves the situation, because measurements are made during the time the transmitter is off. During off-time the only component of emf measured by the receiver is emf_s. Emf_s is determined in the absence of emf_p, greatly improving its accuracy of measurements.

Question.-- Briefly explain how subsurface resistivities are derived from TDEM measurements.

Answer.-- A TDEM system consists of a transmitter and a receiver. The transmitter configuration often used in ground water and environmental applications is a square loop of insulated wire laid on the ground surface (Figure 2). A multi-turn air coil receiver (about 1 m diam) is placed in the center of the loop. The sizes of the transmitter loops employed are mainly dependent upon the required exploration depth and geoelectric section. Typically, the side of a square is about one-half to two-thirds of the required exploration depth. Thus, for exploration depths to about 200 ft, 75 ft by 75 ft transmitter loops may be employed.

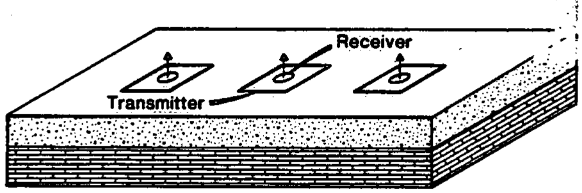

Fig. 2. Transmitter-receiver array in TDEM.

The current waveform driven through the transmitter loops is shown in Figure 1. The waveform consists of equal periods of time-on and time-off. The base frequencies employed in the Geonics instrumentation we employ can be varied from 300 hz, 30 hz, 3 hz and 0.3 hz. These frequencies result in on/off intervals of 0.833, 8.33, 83.3 and 833 msec, respectively.

The current driven through the transmitter loops creates a primary magnetic field. During the rapid current turn-off this primary magnetic field is time-variant and in accordance with Faraday's Law there will be an electromagnetic induction during this time (Figure 1b). This electromagnetic induction in turn results in eddy current flow in the subsurface. The intensity of these currents at a certain time and depth depends on ground conductivity.

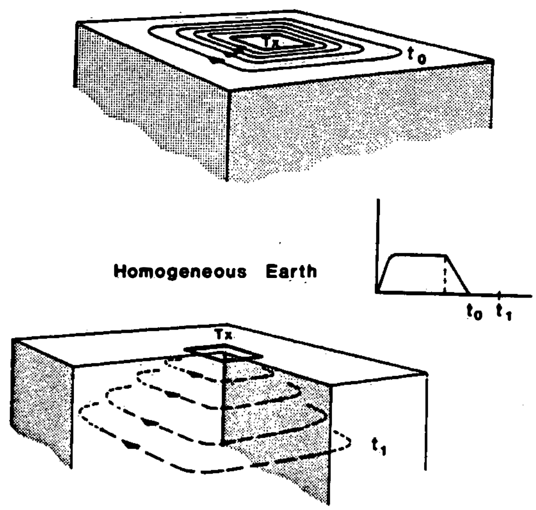

Fig. 3. Current distribution in FDEM at two times after current turn-off.

In near horizontally layered ground, the eddy currents are horizontal closed rings concentric about the center of the transmitter loop. A schematic illustration of these currents is shown in Figure 3. Immediately after turn-off (t_0) the currents are concentrated near the surface, and with increasing time currents are induced at greater depth (t_1).

The receiver measures the emf due the secondary magnetic field caused by these ground eddy currents (Figure 1c). At early time, when the currents are mainly concentrated near the surface, the emf measured will mainly reflect the electrical resistivity of near surface layers. With increasing time, as currents are induced at greater depth, the emf measured will progressively be more influenced by properties of deeper layers. Thus, in TDEM exploration, depth is mainly a function of time of measurement after turn-off.

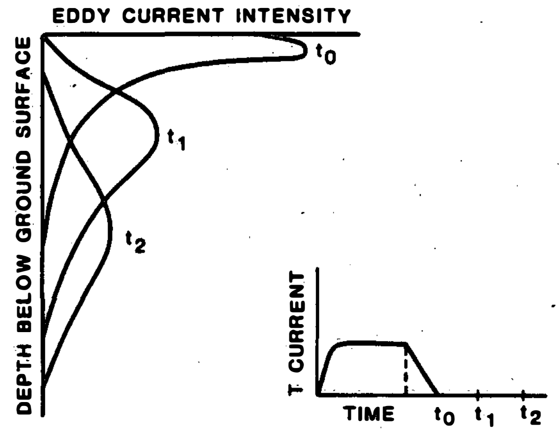

Fig. 4. Schematic illustration of eddy current distribution at different times after turn-off.

Another useful presentation of distribution of current intensity as a function of time is given in Figure 4. At early time, t_0, all currents are concentrated near the surface. At later times (e.g., t_3) the current maxima occur at increasingly greater depth. Thus, from measurements of the decay of emf at one location, the geoelectric section to a substantial depth is obtained.

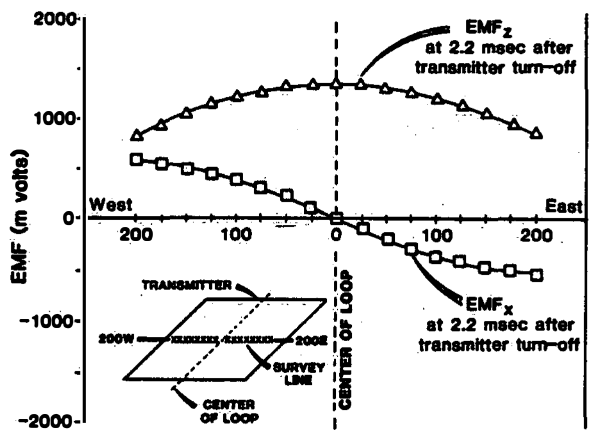

Fig. 5. Spatial behavior of emfs due to vertical (emf_z) and horizontal (emf_x) magnetic field on a profile through the center of square transmitter loop at one time (2.2 millisec) after turn-off.

The emfs caused by square transmitter loops vary with time and distance from the center. Figure 5 shows a typical measured behavior of emfs at a certain time (2.2 milliseconds) after turn-off. At other times the amplitudes will be different, but the spatial behavior is similar. The spatial behavior of the emf_z is relatively flat about the center so that measurements of emf, due to the vertical magnetic field, are relatively insensitive to errors in surveying the center of the loop, or to deviations from a square loop. This is clearly of practical value because it (1. reduces the cost of land surveys and measurement errors, and (2) allows for some flexibility in the field in positioning the measurement stations.

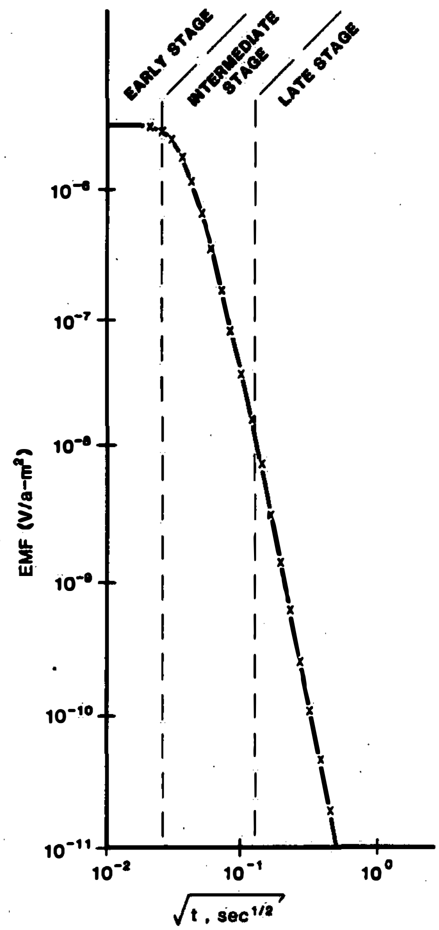

Fig. 6. Typical transient behavior of emf_z in center of square transmitter loop.

Thus, in TDEM soundings, the geoelectric section is derived from measurement of the emf due to the vertical magnetic field (emf_z) as a function of time during the period the transmitter is off. Figure 6 shows a typical behavior of emf_z as a function of time. Emf_z can be seen to decay rapidly with increasing time. One transient decay recorded over a few tens of milliseconds contains information about resistivity layering over a significant depth range.

The emfs, due to the decay of the ground eddy currents, must be measured in the presence of ambient noise sources, such as geomagnetic storms, lightning, 60 hertz powerlines, and other man-made sources. It is common to stack several hundred transient decays to improve signal to noise. Stacking of several hundred transient decays requires only a few seconds, and multiple data sets can be quickly obtained.

The processing and display of TDEM data is in many respects similar to that used in other electrical and electromagnetic methods. The objective of processing TDEM data is to obtain a solution for the resistivity stratification of the subsurface that matches the observed transient.

L022S001

MODEL: 5 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)
2.81	9.3
17.77	33.1
3.01	46.1
39.42	44.8
6.76	

TIMES	DATA LATE MEASURED	CALC LATE	% ERROR
8.90E-05	7.23E+01	7.87E+01	-8.071
1.10E-04	4.75E+01	5.11E+01	-6.997
1.40E-04	3.30E+01	3.38E+01	-2.527
1.77E-04	2.39E+01	2.45E+01	-2.280
2.20E-04	1.83E+01	1.91E+01	-4.201
2.80E-04	1.49E+01	1.55E+01	-3.992
3.55E-04	1.28E+01	1.35E+01	-5.770
4.43E-04	1.13E+01	1.22E+01	-7.412
5.64E-04	1.02E+01	1.05E+01	-3.135
7.13E-04	9.22E+00	9.31E+00	-0.981
8.85E-04	8.14E+00	8.43E+00	-3.402
1.10E-03	7.39E+00	7.52E+00	-1.740
1.41E-03	6.83E+00	6.72E+00	+1.619
1.78E-03	6.36E+00	6.36E+00	+0.002
2.21E-03	6.02E+00	6.06E+00	-0.722
2.83E-03	5.82E+00	5.86E+00	-0.728
3.57E-03	5.80E+00	5.87E+00	-1.050
4.46E-03	5.74E+00	5.82E+00	-1.432
5.67E-03	5.83E+00	5.92E+00	-1.612
7.16E-03	6.01E+00	5.98E+00	+0.543
8.81E-03	5.98E+00	6.05E+00	-1.133
1.10E-02	6.26E+00	6.17E+00	+1.339

RMS ERROR: 5.7275%

Table 1. Inversion table.

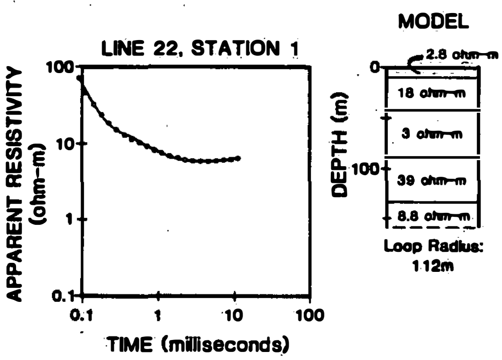

Fig. 7. Example of TDEM apparent resistivity curve and inverted geoelectric section.

The inversion of measured TDEM data into vertical resistivity stratification can be performed on a PC. An example of a data set derived for a sounding is given in Figure 7 and Table 1. In the apparent resistivity curve shown on the left (Figure 7) the measured data at each time gate is superimposed on a model curve of the geoelectric section shown on the right. This geoelectric section represents the best one-dimensional match to the experimental data. In addition to this visual display, an inversion table (Table 1) is obtained that lists (column 4) the error between measured and computed emf at each time gate, as well as an overall RMS error. The data shown on Figure 7 are typical of data quality common to TDEM soundings. Typically, 20 to 30 data points are obtained equally spaced on a logarithmic scale of time. Thus, clearly there is a major difference between TDEM soundings and profiling with the EM-31 and EM-34 (where only a few data points at different effective depths are obtained).

Question.-- If TDEM is a major improvement in electrical geophyics, why has it not been extensively used in ground water and environmental applications?

Answer.-- TDEM has been in common use in the search for base and precious metals, and for deep electrical soundings in support of hydrocarbon and geothermal exploration for about 15 years. The reason for its sparse use so far in ground water and environmental investigations was that no equipment was heretofore available for the often shallow depth (< 100 ft) requirements, common to environmental investigations.

Equipment for shallow exploration recently became available, opening a whole new range of applications for this powerful electrical measurement technique. Figure 8 shows the exploration depth range covered by various instruments.

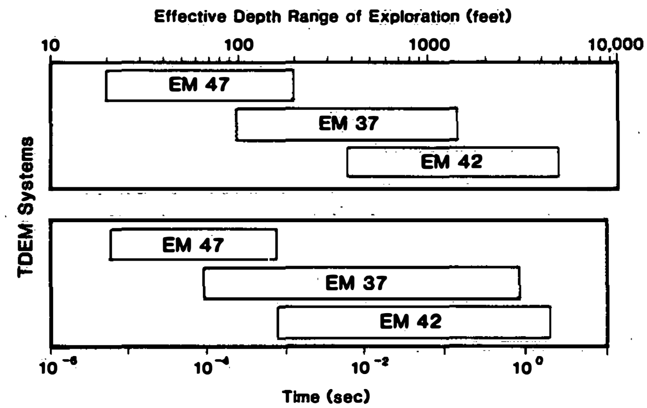

Fig. 8. Effective depth range of exploration and time range of measurement of various TDEM systems.

Question.-- What is geologic noise and why is TDEM less sensitive to such noise?

Answer.-- We define geologic noise as variation in subsurface conditions that obscures the exploration objective. Consider the schematic geologic cross section of the Floridan aquifer (Figure 9). The limestones may be overlain by overburden, likely varying laterally and vertically in soil type and thickness. At some depth in the aquifer an interface between saline and fresh water may occur, and an important exploration objective could be the mapping of this interface. Geologic noise for this objective is the change in soil type and thickness of the overburden. This noise can be very large in direct current resistivity, CSAMT and electromagnetic induction profiling.

Geologic noise is a function of the exploration objective. For example, if the objective in the setting of Figure 9 would have been the mapping of overburden thickness and type (e.g., to delineate areas of prime aquifer recharge), then what was geologic noise before becomes the exploration objective. Geologic noise is often the major cause of poor data quality in geophysical surveys for environmental and ground water applications.

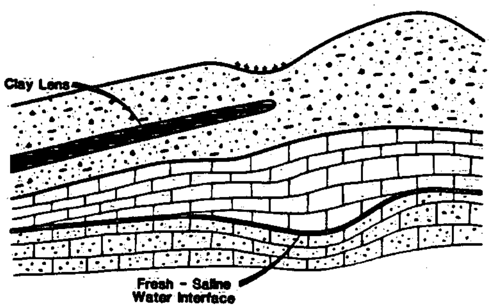

Fig. 9. Schematic geologic section of Floridan aquifer.

Question.-- How does TDEM reduce geologic noise?

Answer.-- This fact can be conceptually explained from Figure 10 where the intensity of eddy current distribution is schematically illustrated as a function of time for the FDEM and TDEM method. At early time (t_0) in TDEM all currents are concentrated near the surface, and near surface formations will largely determine the emf measured. At later time, for example, t_3, currents have largely decayed in near surface layers, and currents dominantly flow at greater depth. The emf measured at time t_3 is near transparent to near surface layers, so that their influence is greatly reduced at time t_3 and later times.

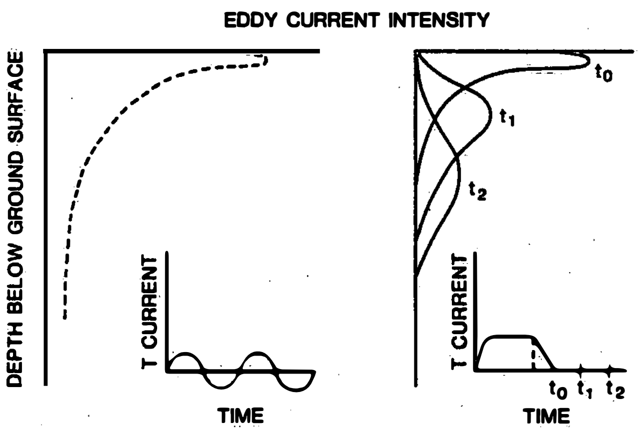

Fig. 10. Eddy current intensity in FDEM and TDEM.

In the FDEM method current intensity is always highest near the surface amplifying the influence of near surface layers.

In summary, geologic noise due to lateral and vertical resistivity variation in TDEM is reduced because:

(a) Exploration depth is mainly a function of time rather than transmitter-receiver separation. The transmitter-receiver separation need not be altered to change exploration depth as is the case in FDEM (EM-31 and EM-34), and direct current resistivity methods.

(b) Relatively small transmitter-receiver separations compared to effective exploration depth are employed.

(c) Measurements at later times are nearly transparent to near surface layers, because eddy currents at later times dominantly flow at greater depth.

Question.-- Can TDEM surveys be effective in mapping fractures and shear zones?

Answer.-- Yes, TDEM can detect contacts, fractures, and shear zones below considerable overburden thickness. The physical concepts of fracture and shear zone mapping are briefly explained.

Electrical and electromagnetic methods are often effective in mapping fractures and shear zones, because fractures and shear zones often are zones of low resistivity in more resistive host rocks. These lower resistivities are generally caused by clay gouge, higher water contents, and alteration in wall rocks. The mapping of fractures and shear zones becomes increasingly more difficult with increasing overburden thickness where outcrops are limited. It is in these situations that geophysical surveys can play an important role.

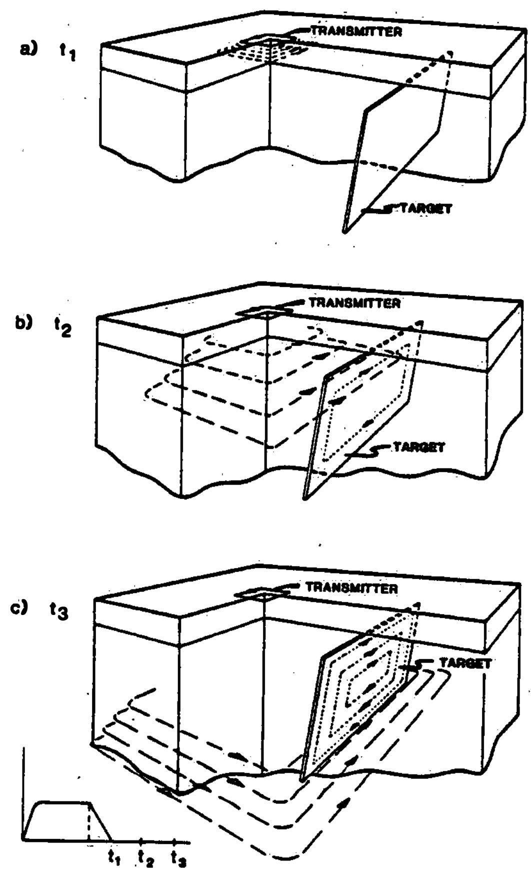

Fig. 11. Illustration of eddy current flow induced in overburden, host rock, and fracture or shear zones at different times.

Thus, in all electrical and electromagnetic methods the geoelectric section is derived by measuring resistance to current flow. We cannot selectively cause current flow in fractures and shear zones, but currents will also be induced in overburden, host rock, fractures and shear zones. The challenge is to isolate the response due to a fracture from the total response, which also contains contributions due to current flow in overburden and host rock.

TDEM is the most effective method for recognizing fractures and shear zones under overburden cover. Figure 11 conceptually explains the physical principles involved. It schematically shows a near vertical fracture zone below overburden cover, and a nearby TDEM source loop induces eddy current flow in the subsurface. At early time (t_0) eddy currents are dominantly situated in the overburden because current flow has not yet reached the fracture. Therefore, a measurement of emf at time, t_0, will not reflect the presence of a fracture zone. At later time currents are induced in the fracture, and because the fracture zone is likely less resistive than adjacent host rock, currents will be preferentially oriented in the fracture plane. In this intermediate time range the emf will contain major contributions due to currents in overburden, host rock and fractures. Currents in overburden may still dominate and fracture zones may be barely detectable. Since the fracture is less resistive than adjacent host rock, currents will decay faster in host rock than in the fracture, and there will be a time range where the fracture has maximum detectability.

To map fractures and shear zones, often different modes of surveying are employed than for determining vertical resistivity stratification (soundings). Figure 12 shows several survey modes. If the strike of the fracture is known a long transmitter loop may be laid out, and profiles are run with a receiver across the fracture zone. Also, a loop-loop array may be employed.

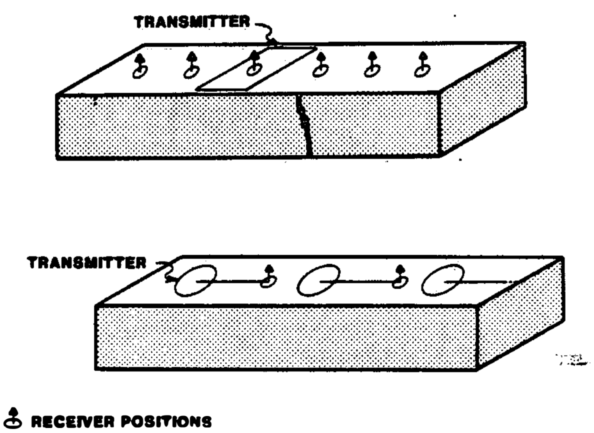

Fig. 12. Transmitter-receiver arrays useful in fracture mapping.

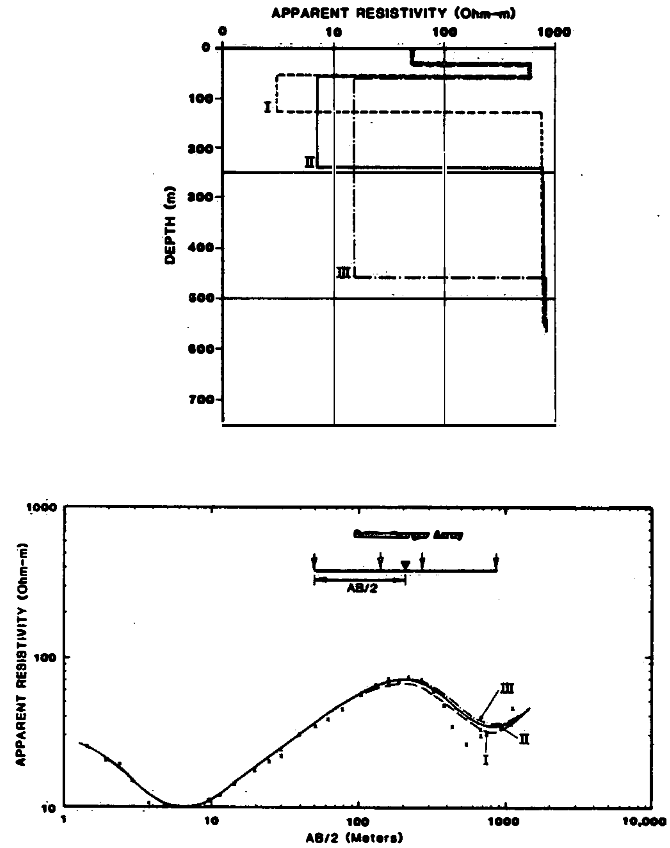

Fig. 13. Schlumberger measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections (b).

Question.-- I am from Missouri. Show me an example comparing TDEM with another electrical measurement technique next to a drill hole.

Answer.-- In a ground water survey on the coastal plain in Israel, one of the exploration objectives was to map the thickness of alluvium overlying a carbonate bedrock. A drill hole at the survey site showed depth to bedrock at about 168 m (550 ft).

The Institute of Petroleum Research and Geophysics, prior to the arrival of our TDEM crew, conducted a Schlumberger resistivity sounding near the drill hole. The results are given in Figure 13. Measurements were made to AL/2-spacing of 2,000 m (an array length of 4,000 m). The measured apparent resistivity data are superimposed on the forward models of three geoelectric sections. The three geoelectric sections are shown on the right. Clearly, the data can be fitted to any of the three models. Yet, depth to bedrock between the three sections was varied by more than 300 m. The Institute, therefore, quickly decided that Schlumberger resistivity soundings were not a viable method, because not only was a large effort required to explore to a depth of 168 m (4,000 m of line length), but its vertical resolution was meaningless.

Measurements at the same location were made with TDEM in 200 m by 200 m transmitter loops, and the results of central-loop TDEM soundings are shown in Figure 14. Again, the measured apparent resistivity curves are superimposed on three forward model curves, and the geoelectric sections of the three model curves are shown on the right. Depth to bedrock in the models is varied by 20 m. It is evident that vertical resolution of determining depth to bedrock is now ± 10 m.

Thus, not only was the physical effort required to sound to a depth of 168 m greatly reduced - only 800 m (4 x 200 m) of wire needed to be laid out, - but the vertical resolution was greatly improved.

Question.-- Summarize for me the potential of TDEM in environmental and ground water geophysics.

Answer.--Electrical surface geophysical methods are an important tool because (1) electrical resistivity is the only readily measureable physical property highly dependent of concentration of dissolved solids (water quality), and (2) electrical resistivity often closely relates to clay content and hydraulic permeability. In the past the vertical and lateral resolution of electrical methods was poor. TDEM techniques are changing that reputation.

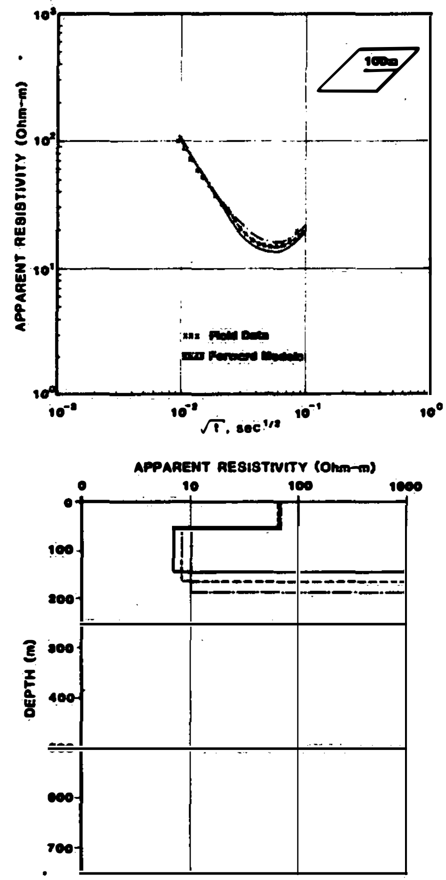

Fig. 14. TDEM measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections.

BLACKHAWK GEOSCIENCES, INC.
17301 WEST COLFAX AVE.
GOLDEN, CO 80401
(303) 278-8700
FAX (303) 278-0789

1N1E

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		152.4	500.0		
22.24	32.9	119.5	392.2	1.5	1.5
395.89	154.3	-34.8	-114.0	0.4	1.9
4.43					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	7.30E+01	6.86E+01	6.509	
2	1.10E-04	6.63E+01	6.40E+01	3.484	
3	1.40E-04	6.01E+01	6.14E+01	-2.065	
4	1.77E-04	5.88E+01	6.11E+01	-3.675	
5	2.20E-04	5.94E+01	6.25E+01	-4.939	
6	2.80E-04	6.17E+01	6.59E+01	-6.299	
7	3.55E-04	6.85E+01	7.06E+01	-2.924	
8	4.43E-04	7.64E+01	7.53E+01	1.493	
9	5.64E-04	8.36E+01	7.86E+01	6.349	
10	7.13E-04	8.53E+01	7.78E+01	9.666	
11	8.81E-04	7.54E+01	7.28E+01	3.525	
12	8.90E-04	7.25E+01	7.25E+01	0.055	
13	1.10E-03	6.63E+01	6.48E+01	2.293	
14	1.10E-03	6.26E+01	6.46E+01	-3.190	
15	1.40E-03	5.29E+01	5.49E+01	-3.538	
16	1.41E-03	5.49E+01	5.46E+01	0.587	
17	1.77E-03	4.40E+01	4.61E+01	-4.464	
18	1.80E-03	4.56E+01	4.56E+01	-0.041	
19	2.20E-03	3.66E+01	3.92E+01	-6.443	
20	2.22E-03	3.92E+01	3.88E+01	0.892	
21	2.80E-03	3.17E+01	3.28E+01	-3.440	
22	3.55E-03	2.58E+01	2.78E+01	-7.030	
23	4.43E-03	2.46E+01	2.39E+01	2.628	
24	5.64E-03	2.25E+01	2.06E+01	9.144	
25	7.13E-03	1.94E+01	1.79E+01	8.210	
26	8.81E-03	1.60E+01	1.59E+01	0.304	
27	1.10E-02	1.45E+01	1.43E+01	1.957	
28	1.41E-02	1.19E+01	1.27E+01	-6.269	

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1106 001N 001E Z OPR XTL H 2 8+100
Ch.21 = 0.095 Ch.22 = 0.089 Ch.23 = 16 Ch.24 =
RMS LOG ERROR: 3.10E-02, ANTILOG YIELDS 7.4073 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

```
P 1   0.22
P 2   0.01   0.00
P 3   0.00   0.00   0.02
T 1  -0.15  -0.01   0.01   0.12
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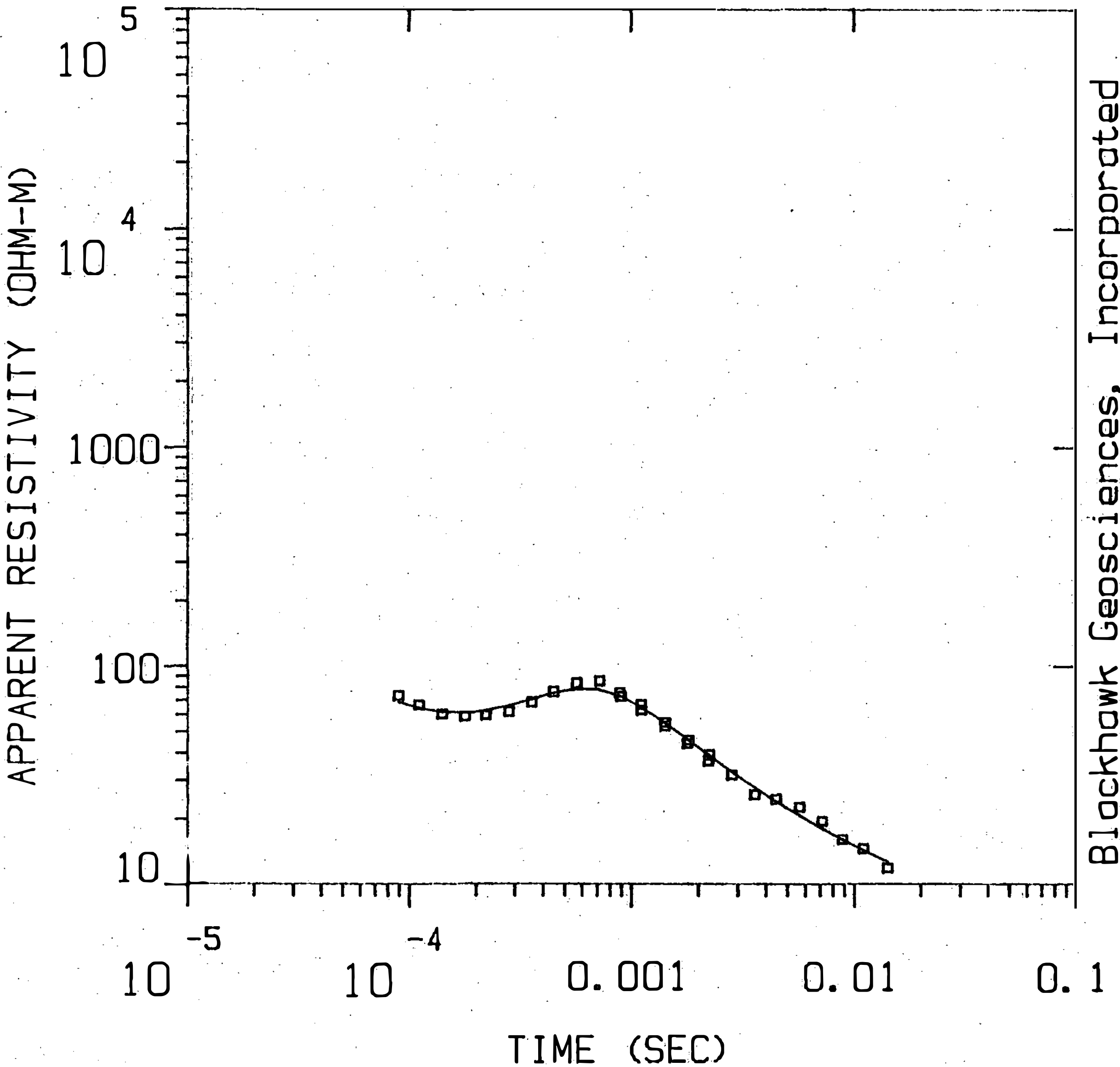
PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	21.232	22.235	23.273
	2	222.623	395.886	3958.861
	3	3.664	4.430	5.239
THICK	1	30.654	32.868	35.439
	2	149.109	154.290	159.487
DEPTH	1	30.654	32.868	35.439
	2	181.999	187.158	192.334

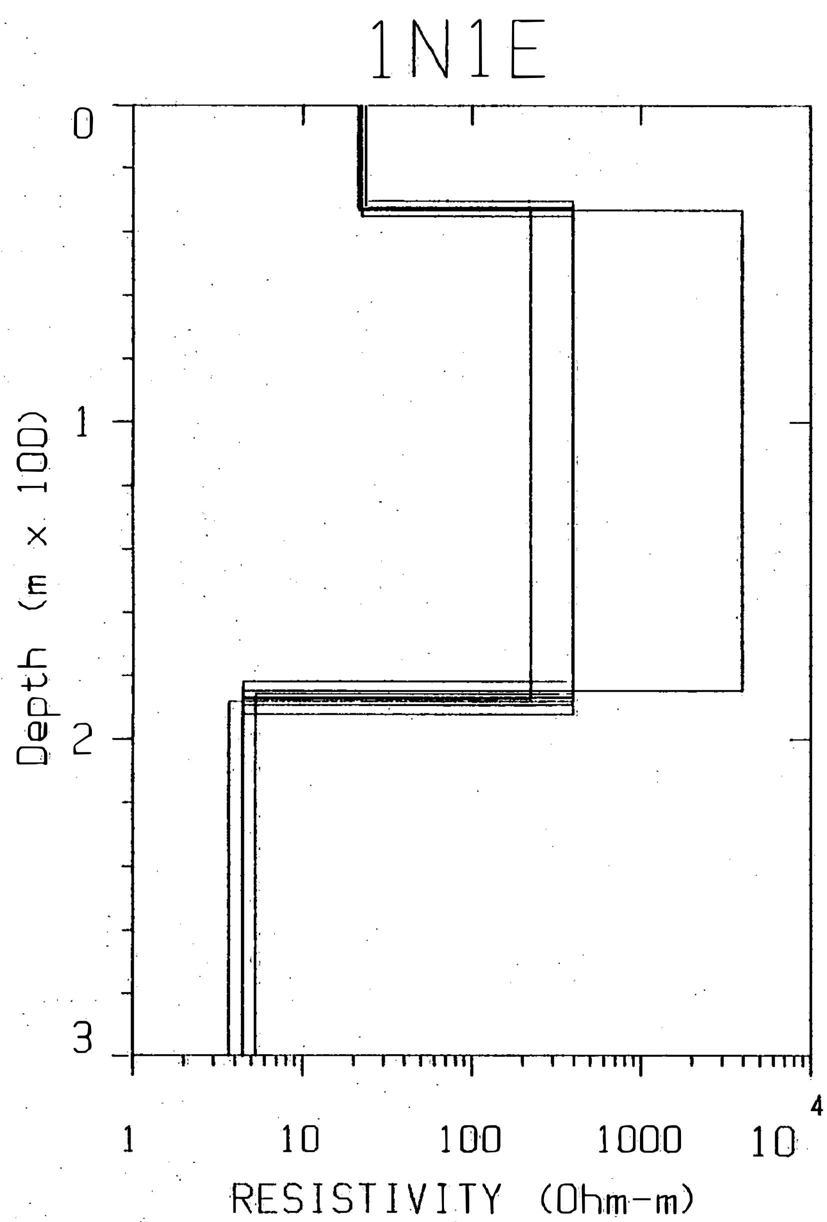
1N1E



MODEL:

22.2 OHM-M	32.9 M
396. OHM-M	154. M
4.43 OHM-M	

% ERROR: 7.41
CALIBRATION: 1
OFFSET: 76.2 M
RAMP: 100.0


1N1E
Depth (m x 100)
0
1
2
3
1
10
100
1000
10^4
RESISTIVITY (Ohm-m)

1N2E

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		147.8	485.0		
38.32	56.7	91.1	299.0	1.5	1.5
187.88	117.3	-26.1	-85.7	0.6	2.1
4.27					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	9.41E+01	9.21E+01	2.171	
2	1.10E-04	8.68E+01	8.50E+01	2.160	
3	1.40E-04	7.89E+01	8.01E+01	-1.436	
4	1.77E-04	7.67E+01	7.79E+01	-1.555	
5	2.20E-04	7.69E+01	7.78E+01	-1.086	
6	2.80E-04	7.78E+01	7.92E+01	-1.699	
7	3.55E-04	8.08E+01	8.12E+01	-0.503	
8	4.43E-04	8.23E+01	8.22E+01	0.170	
9	5.64E-04	8.20E+01	8.03E+01	2.161	
10	7.13E-04	7.80E+01	7.45E+01	4.659	
11	8.81E-04	6.74E+01	6.68E+01	0.865	
12	8.90E-04	6.39E+01	6.64E+01	-3.706	
13	1.10E-03	5.93E+01	5.79E+01	2.501	
14	1.10E-03	5.65E+01	5.77E+01	-2.197	
15	1.40E-03	4.71E+01	4.84E+01	-2.771	
16	1.41E-03	5.00E+01	4.81E+01	3.752	
17	1.77E-03	3.95E+01	4.06E+01	-2.765	
18	1.80E-03	4.24E+01	4.02E+01	5.639	
19	2.20E-03	3.36E+01	3.45E+01	-2.646	
20	2.80E-03	2.85E+01	2.90E+01	-1.950	
21	3.55E-03	2.40E+01	2.47E+01	-2.936	
22	4.43E-03	2.04E+01	2.14E+01	-4.604	
23	5.64E-03	1.88E+01	1.85E+01	1.824	
24	7.13E-03	1.71E+01	1.62E+01	5.723	

R: 76. X: 0. Y: 76. DL: 152. REQ: 84. CF: 1.0000
CLHZ ARRAY, 24 DATA POINTS, RAMP: 100.0 MICROSEC, DATA: 1N2E
1106 001N 002E Z OPR XTL H 2 8+100
Ch.21 = 0.095 Ch.22 = 0.089 Ch.23 = 16 Ch.24 =
RMS LOG ERROR: 1.91E-02, ANTILOG YIELDS 4.4849 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

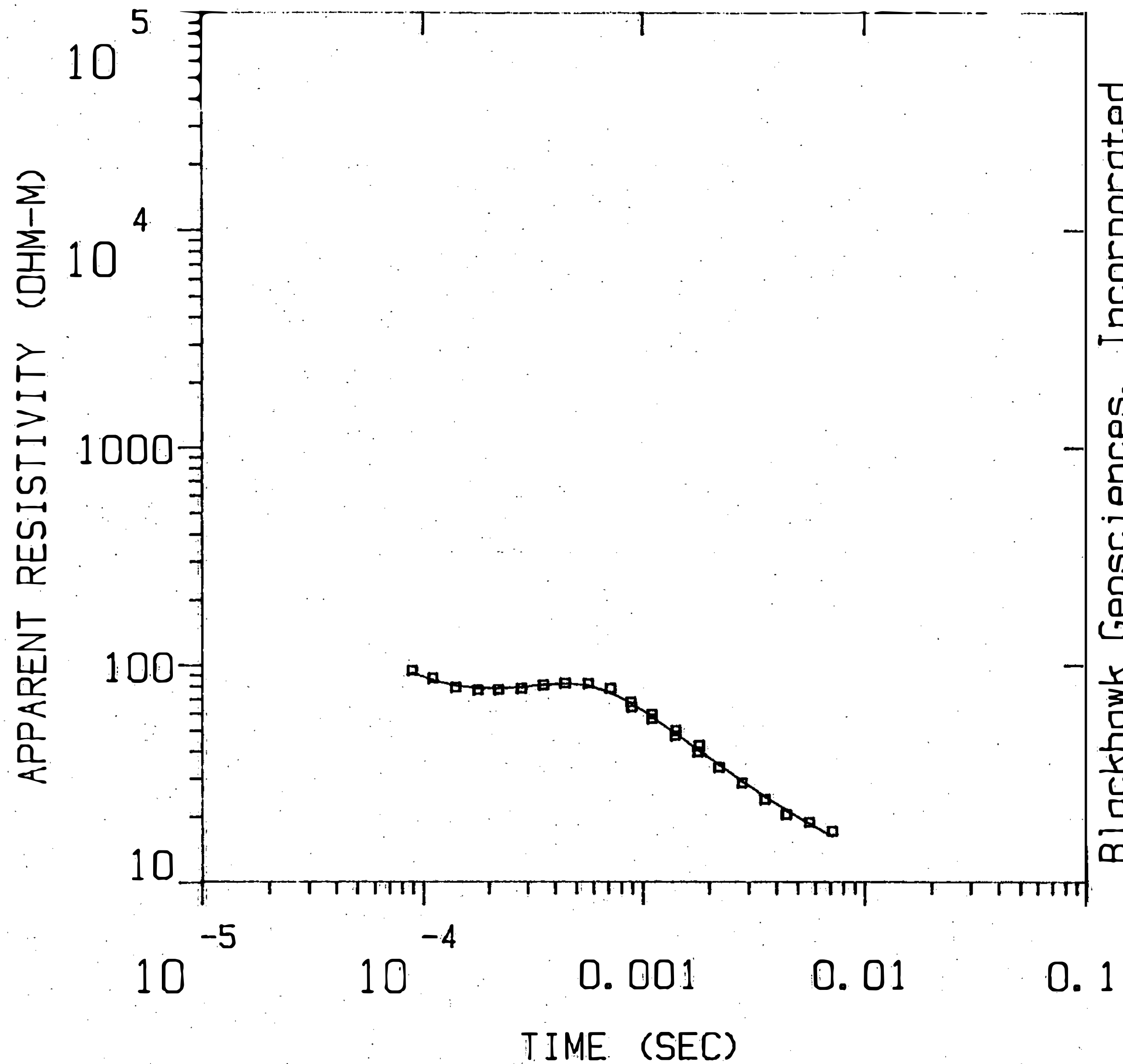
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.98				
P 2	-0.03	0.08			
P 3	0.01	-0.02	0.95		
T 1	-0.04	-0.21	0.02	0.87	
T 2	0.02	0.12	0.00	0.06	0.97
	P 1	P 2	P 3	T 1	T 2

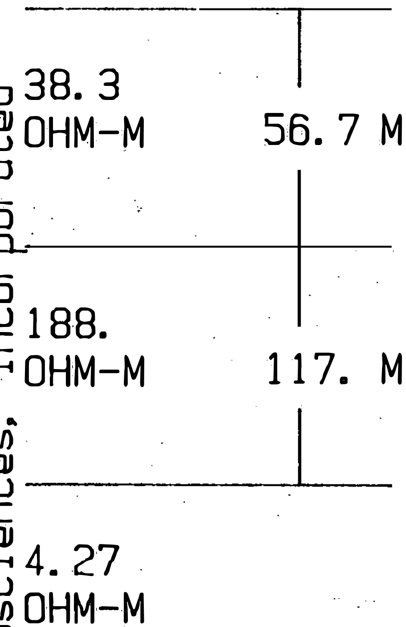
PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	35.353	38.317	41.041
	2	125.516	187.882	332.499
	3	3.846	4.268	4.676
THICK	1	45.809	56.681	69.715
	2	105.768	117.257	128.874
DEPTH	1	45.809	56.681	69.715
	2	172.146	173.938	176.290

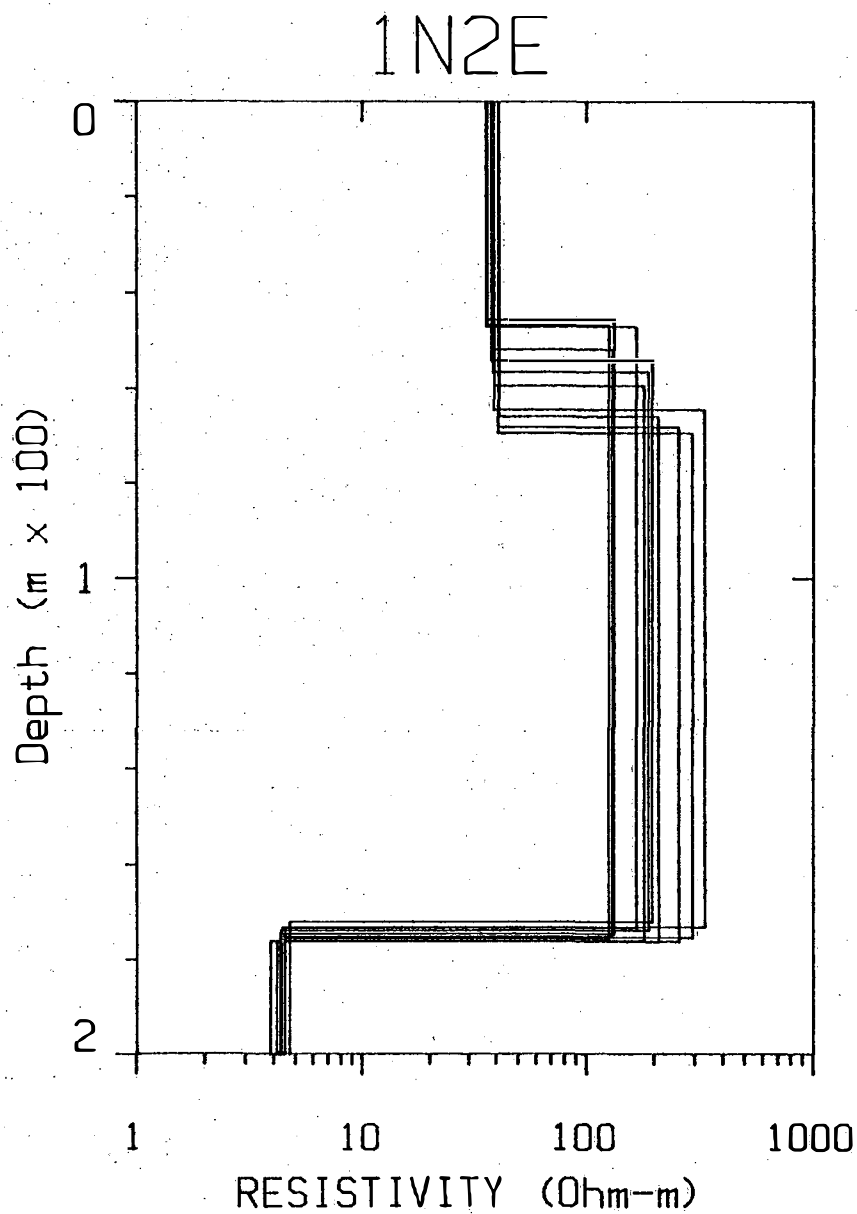
1N2E



MODEL:



% ERROR: 4.48
CALIBRATION: 1
OFFSET: 76.2 M
RAMP: 100.0



1N2E
Depth (m x 100)
0
1
2
1
10
100
1000
RESISTIVITY (Ohm-m)

1N3E

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		210.3	690.0		
44.45	82.2	128.1	420.2	1.8	1.8
378.47	172.1	-44.0	-144.4	0.5	2.3
2.92					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	9.45E+01	8.82E+01	7.212	
2	1.40E-04	8.35E+01	8.07E+01	3.518	
3	1.77E-04	7.52E+01	7.63E+01	-1.353	
4	2.20E-04	7.18E+01	7.44E+01	-3.392	
5	2.80E-04	7.04E+01	7.45E+01	-5.557	
6	3.55E-04	7.31E+01	7.69E+01	-4.928	
7	4.43E-04	7.88E+01	8.11E+01	-2.815	
8	5.64E-04	8.81E+01	8.73E+01	0.957	
9	7.13E-04	1.01E+02	9.34E+01	7.572	
10	8.81E-04	9.79E+01	9.68E+01	1.160	
11	1.10E-03	9.59E+01	9.53E+01	0.609	
12	1.41E-03	8.90E+01	8.66E+01	2.754	
13	1.80E-03	7.26E+01	7.40E+01	-1.921	
14	2.22E-03	6.29E+01	6.25E+01	0.652	
15	2.85E-03	5.14E+01	5.06E+01	1.483	
16	3.60E-03	4.50E+01	4.15E+01	8.441	
17	4.43E-03	3.41E+01	3.48E+01	-2.032	
18	4.49E-03	3.52E+01	3.45E+01	2.291	
19	5.64E-03	2.79E+01	2.86E+01	-2.421	
20	5.70E-03	2.71E+01	2.84E+01	-4.498	
21	7.13E-03	2.37E+01	2.39E+01	-0.619	
22	7.19E-03	2.10E+01	2.37E+01	-11.456	
23	8.81E-03	2.02E+01	2.04E+01	-0.957	
24	1.10E-02	1.72E+01	1.75E+01	-1.701	
25	1.41E-02	1.51E+01	1.48E+01	1.983	
26	1.80E-02	1.35E+01	1.28E+01	5.647	
27	2.22E-02	1.17E+01	1.13E+01	3.398	
28	2.85E-02	9.84E+00	9.88E+00	-0.400	
29	3.60E-02	8.87E+00	8.81E+00	0.715	

R: 76. X: 0. Y: 76. DL: 152. REQ: 84. CF: 1.0000
CLHZ ARRAY, 29 DATA POINTS, RAMP: 100.0 MICROSEC, DATA: 1N3E
1206 001N 003E Z OPR XTL L 4 8+1000
Ch.21 = 0.1 Ch.22 = 0.89 Ch.23 = 16 Ch.24 = 232
RMS LOG ERROR: 2.73E-02, ANTILOG YIELDS 6.4961 %
LATE TIME PARAMETERS

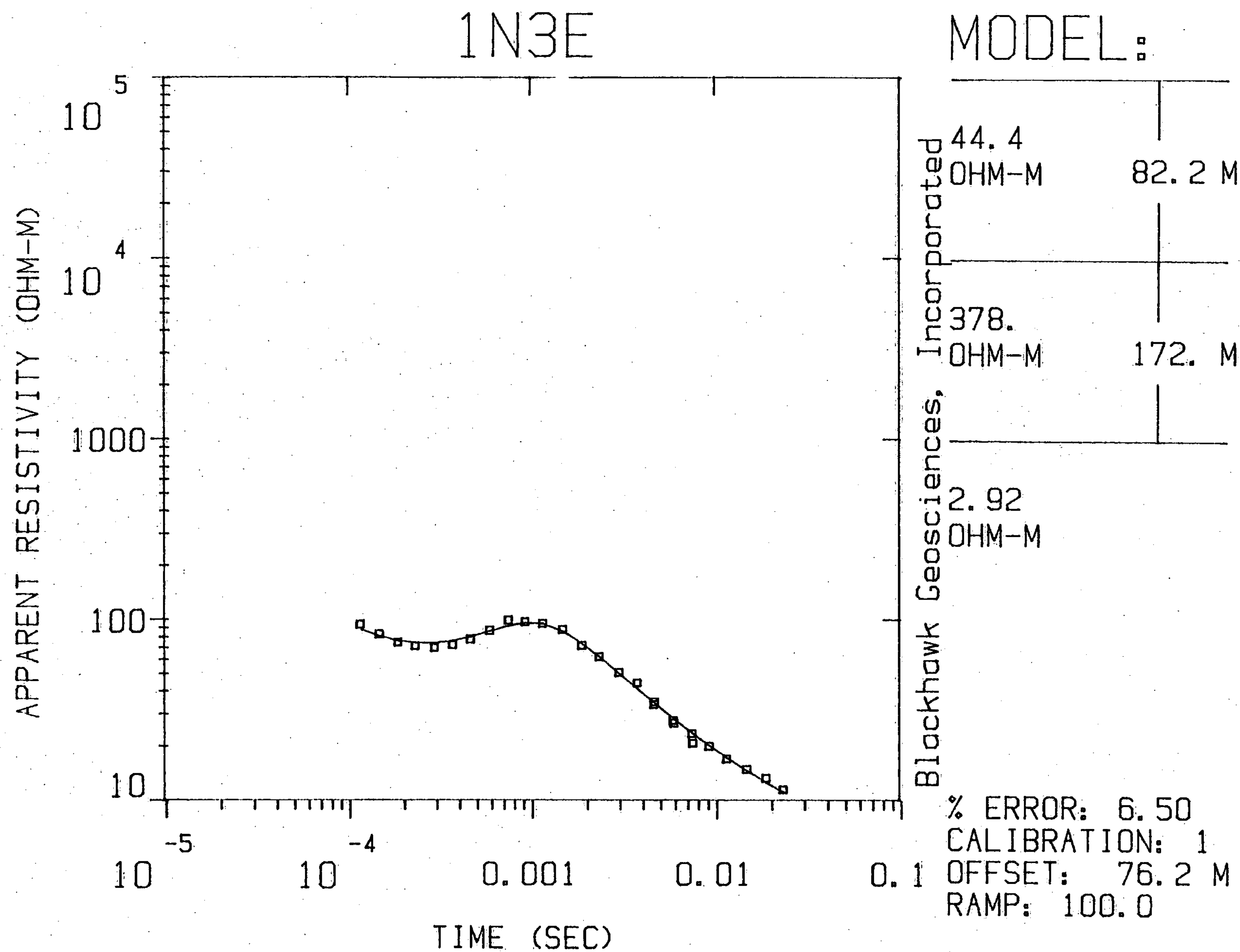
* Blackhawk Geosciences, Incorporated *

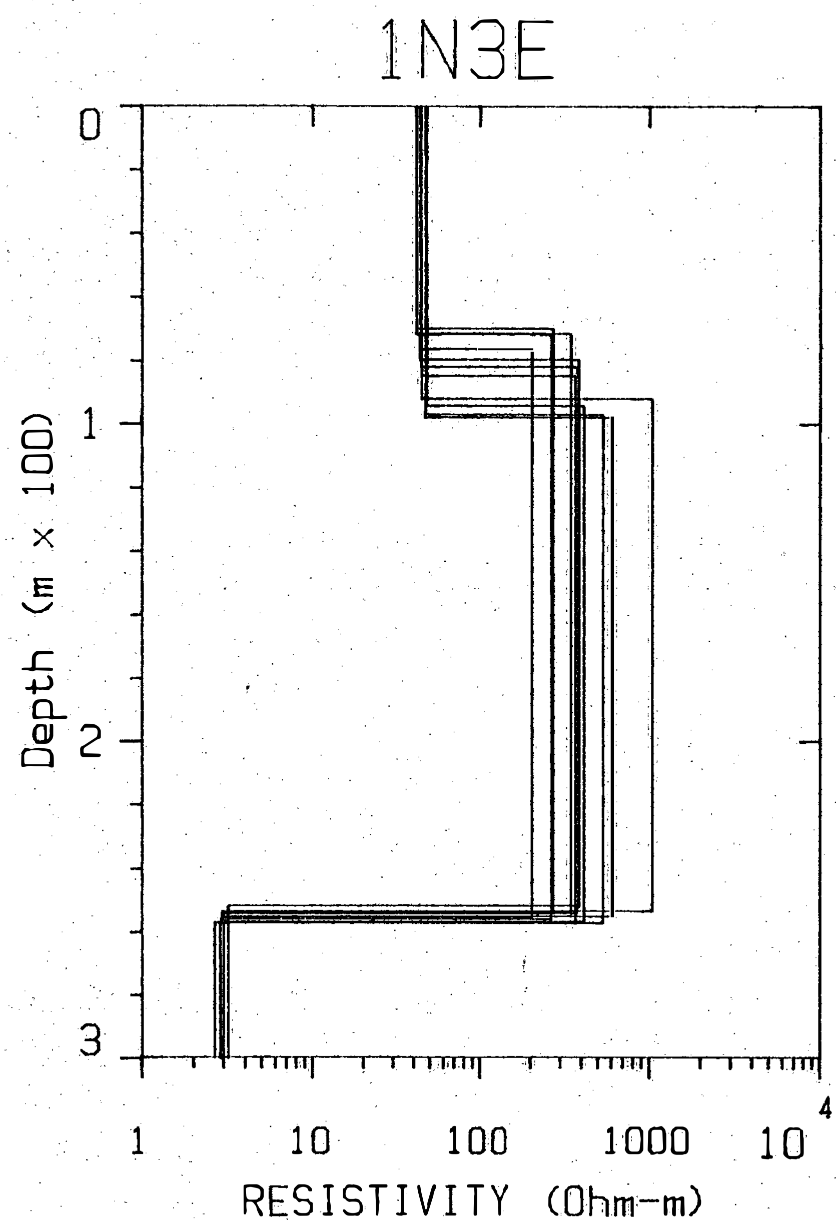
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER
P 1 0.99
P 2 -0.01 0.92
P 3 0.00 -0.01 0.97
T 1 -0.02 -0.11 0.01 0.95

T 2 0.01 0.06 0.00 0.02 0.99
P 1 P 2 P 3 T 1 T 2

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	41.528	44.450	47.712
	2	203.471	378.472	1038.240
	3	2.642	2.915	3.171
THICK	1	70.270	82.226	98.204
	2	157.092	172.086	184.156
DEPTH	1	70.270	82.226	98.204
	2	251.911	254.312	257.354


1N3E
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
44.4
OHM-M
82.2 M
378.
OHM-M
172. M
2.92
OHM-M
% ERROR: 6.50
CALIBRATION: 1
OFFSET: 76.2 M
RAMP: 100.0


1N3E
0
1
2
3
Depth (m x 100)
1
10
100
1000
10^4
RESISTIVITY (Ohm-m)

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		231.6	760.0		
42.16	149.5	82.2	269.5	3.5	3.5
182.77	70.4	11.7	38.4	0.4	3.9
4.01					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	1.35E+02	1.25E+02	8.571	
2	1.40E-04	1.11E+02	1.05E+02	5.302	
3	1.77E-04	9.08E+01	9.09E+01	-0.125	
4	2.20E-04	7.99E+01	8.12E+01	-1.662	
5	2.80E-04	7.08E+01	7.36E+01	-3.870	
6	3.55E-04	6.60E+01	6.88E+01	-4.029	
7	4.43E-04	6.43E+01	6.61E+01	-2.764	
8	5.64E-04	6.44E+01	6.47E+01	-0.553	
9	7.13E-04	6.54E+01	6.41E+01	1.981	
10	8.81E-04	6.33E+01	6.33E+01	0.077	
11	1.10E-03	6.24E+01	6.12E+01	1.826	
12	1.41E-03	5.76E+01	5.67E+01	1.554	
13	1.80E-03	5.11E+01	5.05E+01	1.108	
14	2.22E-03	4.39E+01	4.44E+01	-1.098	
15	2.85E-03	3.65E+01	3.76E+01	-2.838	
16	3.60E-03	3.13E+01	3.19E+01	-2.152	
17	4.49E-03	2.73E+01	2.74E+01	-0.316	
18	5.70E-03	2.41E+01	2.34E+01	2.890	

R: 114. X: 0. Y: 114. DL: 229. REQ: 127. CF: 1.0000
CLHZ ARRAY, 18 DATA POINTS, RAMP: 160.0 MICROSEC, DATA: 1N4E
1206 001N 004E Z OPR XTL H 2 8+100
Ch.21 = 0.16 Ch.22 = 0.089 Ch.23 = 19 Ch.24 = 5
RMS LOG ERROR: 2.01E-02, ANTILOG YIELDS 4.7316 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

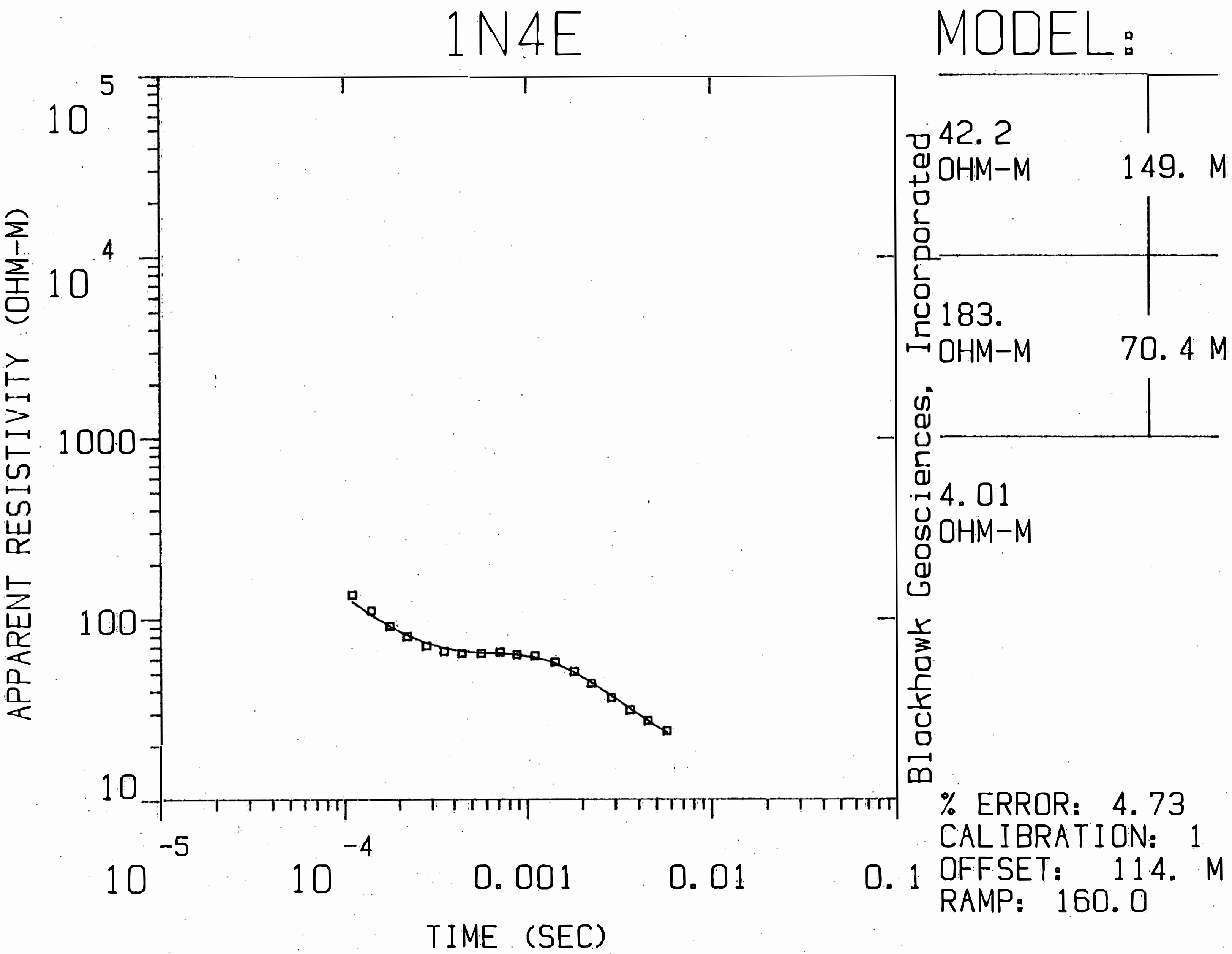
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

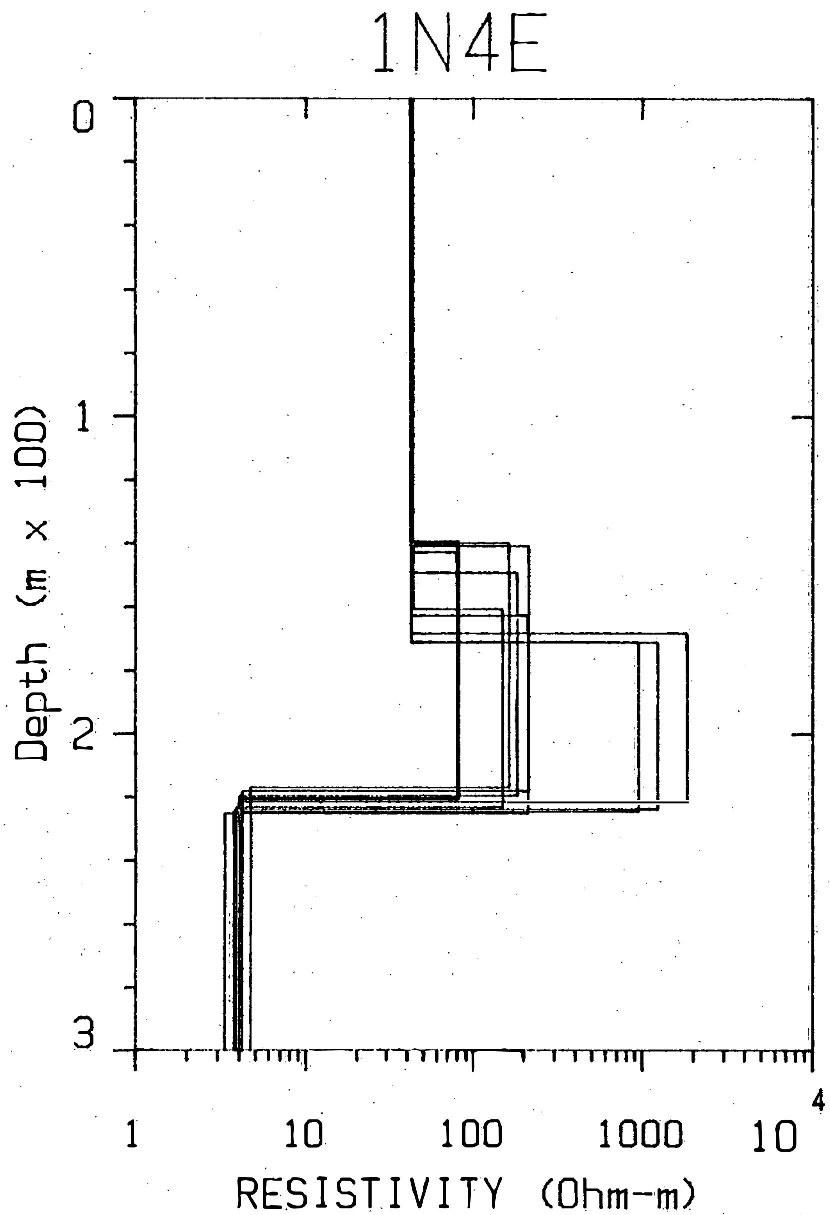
P 1	1.00				
P 2	0.00	0.02			
P 3	0.00	0.00	0.99		
T 1	0.00	-0.05	0.00	1.00	
T 2	0.00	0.12	0.00	0.01	0.98
	P 1	P 2	P 3	T 1	T 2

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	41.526	42.163	43.010
	2	79.225	182.771	1827.710
	3	3.284	4.007	4.64[illegible]

THICK	1	139.744	149.492	171.445
	2	52.707	70.449	80.688
DEPTH	1	139.744	149.492	171.445
	2	217.295	219.941	225.376


1N4E
MODEL:
42.2
OHM-M
149. M
183.
OHM-M
70.4 M
4.01
OHM-M
% ERROR: 4.73
CALIBRATION: 1
OFFSET: 114. M
RAMP: 160.0
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated


1N4E
Depth (m x 100)
0
1
2
3
1
10
100
1000
10^4
RESISTIVITY (Ohm-m)

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		173.7	570.0		
61.72	97.0	76.7	251.8	1.6	1.6
202.34	98.4	-21.7	-71.2	0.5	2.1
7.68					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.29E+02	1.31E+02	-1.580	
2	1.10E-04	1.18E+02	1.20E+02	-1.316	
3	1.40E-04	1.12E+02	1.11E+02	0.347	
4	1.77E-04	1.06E+02	1.06E+02	0.261	
5	2.20E-04	1.05E+02	1.03E+02	1.380	
6	2.80E-04	1.02E+02	1.02E+02	0.252	
7	3.55E-04	1.02E+02	1.02E+02	-0.202	
8	4.43E-04	1.01E+02	1.01E+02	0.204	
9	5.64E-04	9.69E+01	9.60E+01	0.953	
10	7.13E-04	9.07E+01	8.97E+01	1.148	
11	8.81E-04	7.80E+01	8.14E+01	-4.268	
12	1.10E-03	6.94E+01	7.07E+01	-1.867	
13	1.41E-03	6.01E+01	6.07E+01	-0.976	
14	1.80E-03	5.20E+01	5.18E+01	0.405	
15	2.22E-03	4.65E+01	4.48E+01	3.798	
16	2.85E-03	4.09E+01	3.84E+01	6.556	
17	3.55E-03	3.30E+01	3.38E+01	-2.508	
18	4.43E-03	2.89E+01	2.97E+01	-2.557	
19	5.64E-03	2.66E+01	2.63E+01	1.124	
20	7.13E-03	2.38E+01	2.34E+01	1.753	
21	8.81E-03	2.07E+01	2.12E+01	-2.072	
22	1.10E-02	1.92E+01	1.95E+01	-1.292	

R: 76. X: 0. Y: 76. DL: 152. REQ: 84. CF: 1.0000
CLHZ ARRAY, 22 DATA POINTS, RAMP: 100.0 MICROSEC, DATA: 1N5E
1306 001N 005E Z OPR XTL H 2 8+100
Ch.21 = 0.1 Ch.22 = 0.089 Ch.23 = 16 Ch.24 = 23
RMS LOG ERROR: 1.46E-02, ANTILOG YIELDS 3.4131 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

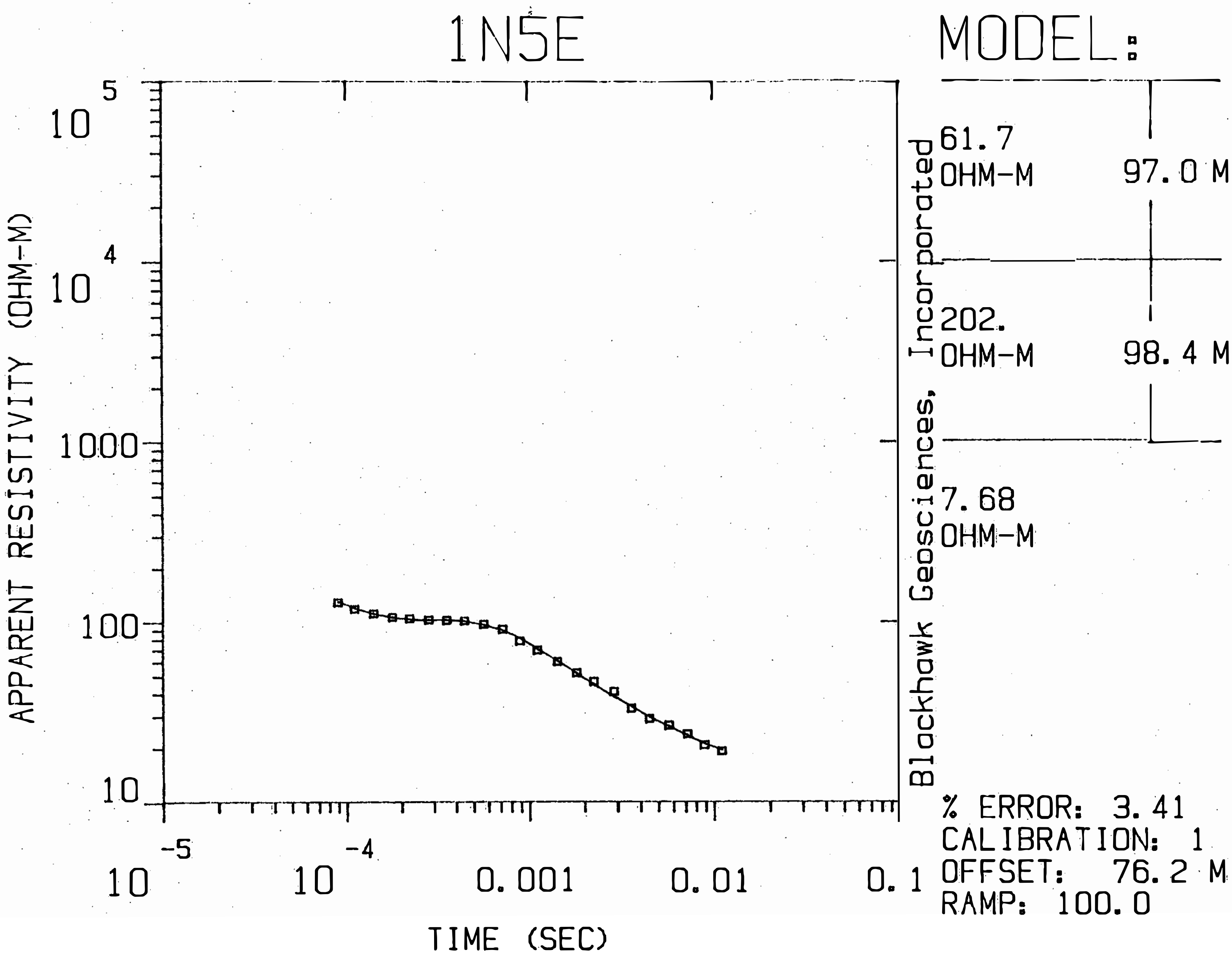
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00				
P 2	0.00	0.06			
P 3	0.00	-0.01	0.98		
T 1	-0.01	-0.15	0.01	0.92	
T 2	0.01	0.18	0.00	0.07	0.93
	P 1	P 2	P 3	T 1	T 2

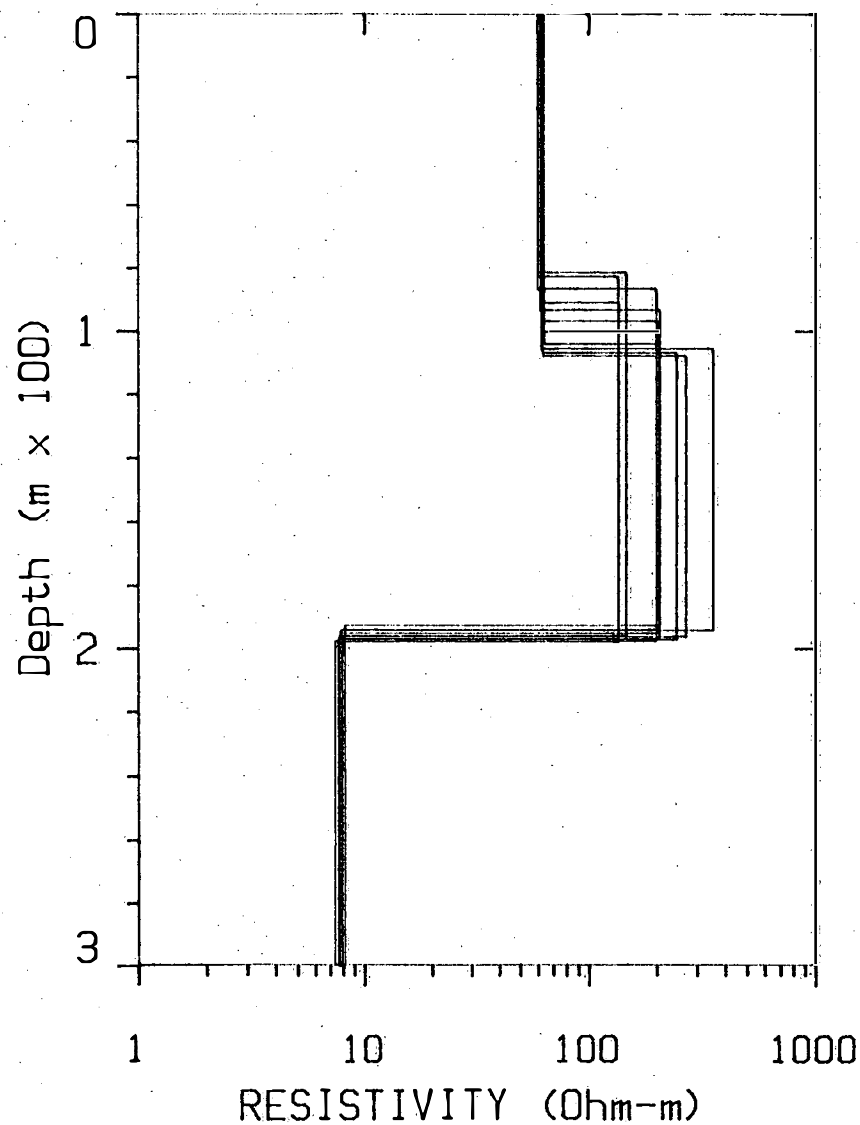
PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	59.589	61.717	63.133
	2	134.616	202.340	353.815
	3	7.321	7.683	8.091

THICK	1	81.595	96.995	108.161
	2	88.299	98.435	115.189
DEPTH	1	81.595	96.995	108.161
	2	192.955	195.431	198.042


1N5E
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
61.7 OHM-M
97.0 M
202. OHM-M
98.4 M
7.68 OHM-M
% ERROR: 3.41
CALIBRATION: 1
OFFSET: 76.2 M
RAMP: 100.0

1N5E



1N6E

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		274.3	900.0		
66.90	53.9	220.5	723.3	0.8	0.8
27.91	151.6	68.9	226.1	5.4	6.2
2.54					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.52E+02	1.45E+02	4.445	
2	1.10E-04	1.27E+02	1.24E+02	2.731	
3	1.40E-04	1.05E+02	1.04E+02	0.568	
4	1.77E-04	8.75E+01	8.96E+01	-2.262	
5	2.20E-04	7.64E+01	7.90E+01	-3.276	
6	2.80E-04	6.73E+01	7.01E+01	-3.994	
7	3.55E-04	6.21E+01	6.38E+01	-2.661	
8	4.43E-04	5.91E+01	5.96E+01	-0.875	
9	5.64E-04	5.73E+01	5.66E+01	1.361	
10	7.13E-04	5.56E+01	5.44E+01	2.206	
11	8.81E-04	5.26E+01	5.25E+01	0.357	
12	1.10E-03	4.98E+01	4.98E+01	0.019	
13	1.41E-03	4.63E+01	4.54E+01	1.916	
14	1.80E-03	4.11E+01	4.01E+01	2.478	
15	2.22E-03	3.50E+01	3.51E+01	-0.135	
16	2.85E-03	2.93E+01	2.95E+01	-0.683	
17	3.60E-03	2.43E+01	2.49E+01	-2.175	
18	4.49E-03	2.08E+01	2.12E+01	-1.732	
19	5.70E-03	1.77E+01	1.79E+01	-1.013	
20	7.19E-03	1.58E+01	1.52E+01	3.888	

R: 87. X: 0. Y: 87. DL: 174. REQ: 97. CF: 1.0000
CLHZ ARRAY, 20 DATA POINTS, RAMP: 125.0 MICROSEC, DATA: 1N6E
2906 001N 006E Z OPR XTL H 3 8+100
Ch.21 = 0.125 Ch.22 = 0.089 Ch.23 = 16 Ch.24 =
RMS LOG ERROR: 1.51E-02, ANTILOG YIELDS 3.5432 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

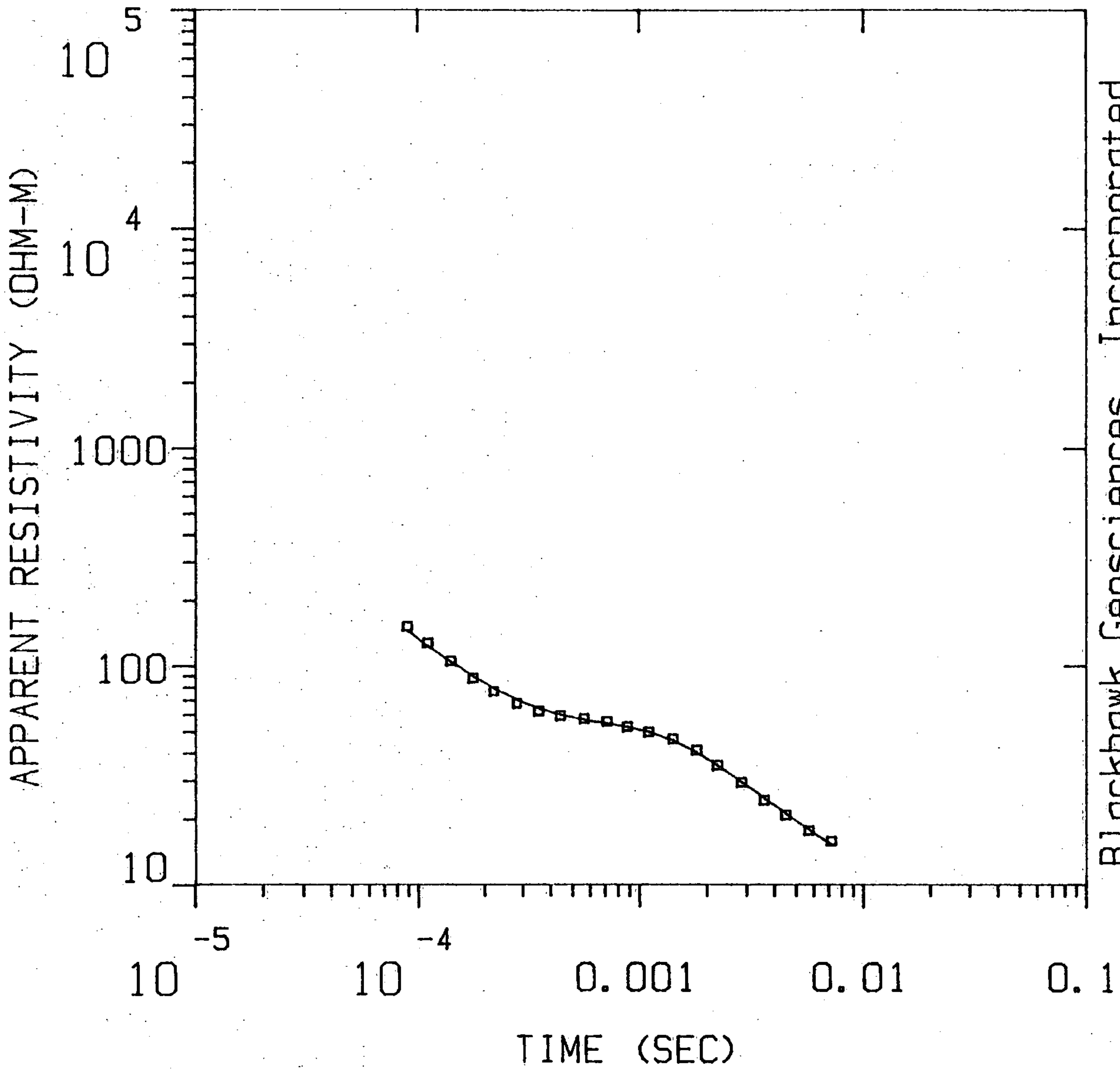
	P 1	P 2	P 3	T 1	T 2
P 1	0.54				
P 2	0.02	0.79			
P 3	0.03	-0.10	0.19		
T 1	0.33	0.20	0.01	0.39	
T 2	-0.13	-0.05	0.05	0.20	0.88

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

	LAYER	MINIMUM	BEST	MAXIMUM
RHO	1	63.978	66.902	88.300
	2	[illegible]	[illegible]	[illegible]

	3	2.076	1.835	1.778
THICK	1	44.079	53.857	57.351
	2	148.246	151.550	163.534
DEPTH	1	44.079	53.857	57.351
	2	204.123	205.407	208.206

1N6E



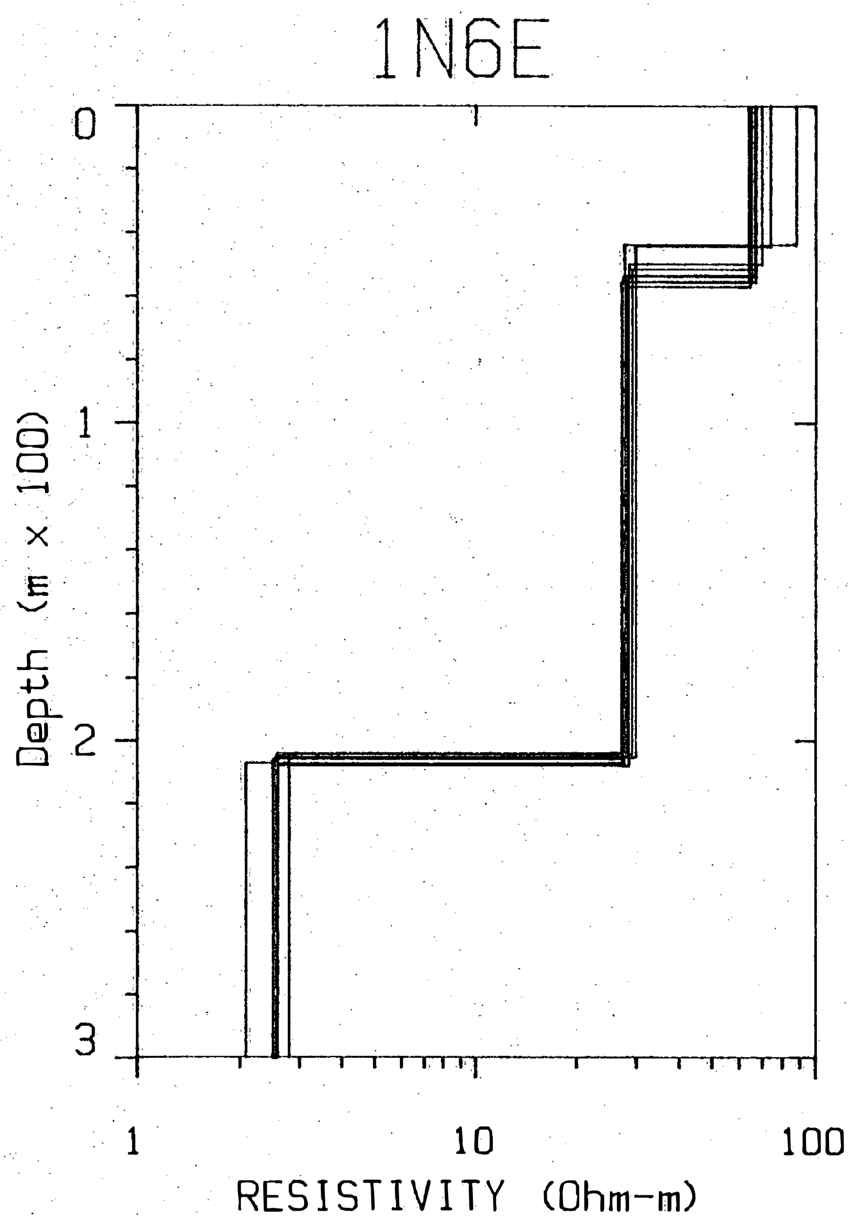
MODEL:

66.9 OHM-M 53.9 M

27.9 OHM-M 152. M

2.54 OHM-M

% ERROR: 3.54
CALIBRATION: 1
OFFSET: 86.9 M
RAMP: 125.0


1N6E
Depth (m x 100)
0
1
2
3
1
10
100
RESISTIVITY (Ohm-m)

1N7E

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		195.1	640.0		
41.11	97.9	97.2	318.9	2.4	2.4
322.41	65.4	31.8	104.2	0.2	2.6
4.94					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.03E+02	1.05E+02	-2.031	
2	1.10E-04	9.20E+01	9.32E+01	-1.314	
3	1.40E-04	8.29E+01	8.32E+01	-0.326	
4	1.77E-04	7.68E+01	7.66E+01	0.287	
5	2.20E-04	7.38E+01	7.27E+01	1.465	
6	2.80E-04	7.10E+01	7.02E+01	1.083	
7	3.55E-04	6.97E+01	6.88E+01	1.251	
8	4.43E-04	6.83E+01	6.75E+01	1.112	
9	5.64E-04	6.45E+01	6.50E+01	-0.805	
10	7.13E-04	5.99E+01	6.07E+01	-1.166	
11	8.81E-04	5.34E+01	5.53E+01	-3.424	
12	1.10E-03	4.77E+01	4.89E+01	-2.616	
13	1.41E-03	4.28E+01	4.17E+01	2.691	
14	1.80E-03	3.58E+01	3.55E+01	0.966	
15	2.22E-03	3.25E+01	3.08E+01	5.541	
16	2.85E-03	2.63E+01	2.62E+01	0.205	
17	3.60E-03	2.27E+01	2.27E+01	-0.126	
18	4.49E-03	1.97E+01	1.99E+01	-1.106	
19	5.70E-03	1.72E+01	1.75E+01	-1.717	
20	7.19E-03	1.55E+01	1.56E+01	-0.496	

R: 81. X: 0. Y: 81. DL: 162. REQ: 90. CF: 1.0000
CLHZ ARRAY, 20 DATA POINTS, RAMP: 130.0 MICROSEC, DATA: 1N7E
2906 001N 007E Z OPR XTL H 3 8+100
Ch.21 = 0.13 Ch.22 = 0.089 Ch.23 = 17 Ch.24 = 2
RMS LOG ERROR: 1.26E-02, ANTILOG YIELDS 2.9470 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

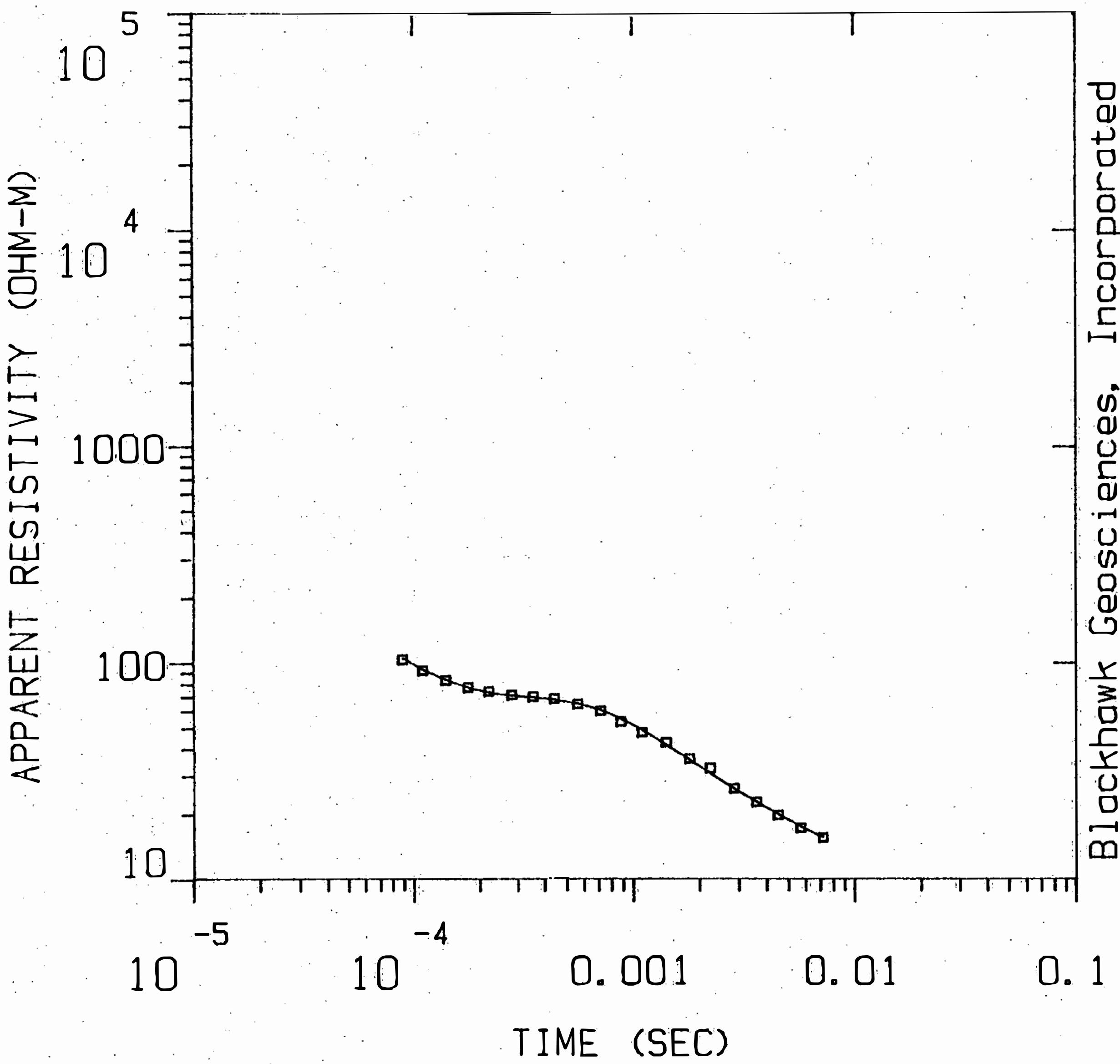
P 1	1.00				
P 2	0.00	0.01			
P 3	0.00	0.00	1.00		
T 1	0.00	-0.04	0.00	1.00	
T 2	0.00	0.06	0.00	0.00	0.99
	P 1	P 2	P 3	T 1	T 2

PARAMETER BOUNDS FROM EQUIVALENCE ANALYSIS

LAYER		MINIMUM	BEST	MAXIMUM
RHO	1	40.038	41.114	41.691
	2	[illegible]	[illegible]	[illegible]

	2	[illegible]	[illegible]	[illegible]
	3	4.675	4.936	5.285
THICK	1	89.413	97.868	104.225
	2	59.687	65.444	72.516
DEPTH	1	89.413	97.868	104.225
	2	161.041	163.311	165.254

1N7E



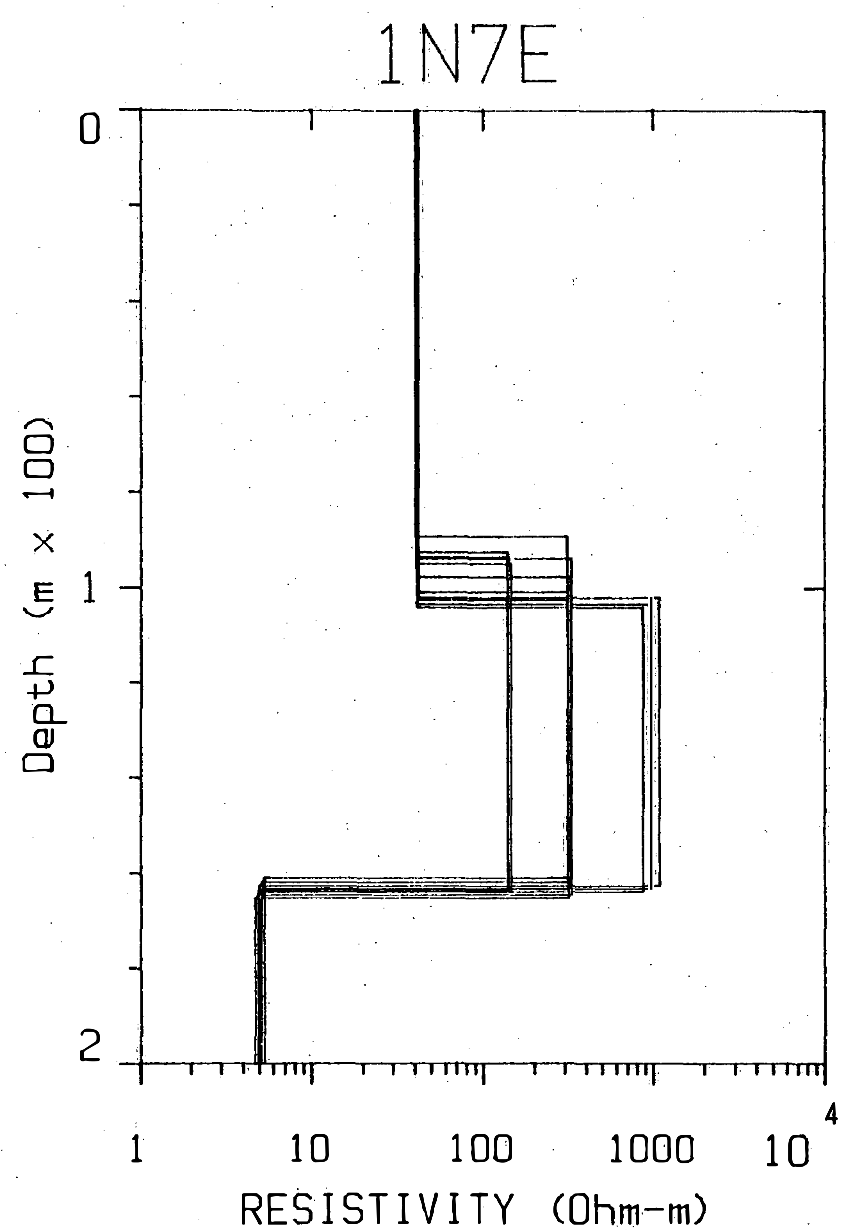
MODEL:

41.1 OHM-M 97.9 M

322. OHM-M 65.4 M

4.94 OHM-M

% ERROR: 2.95
CALIBRATION: 1
OFFSET: 80.9 M
RAMP: 130.0


1N7E
Depth (m x 100)
0
1
2
1
10
100
1000
10^4
RESISTIVITY (Ohm-m)